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AIRCREW OXYGEN SYSTEM DEVELOPMENT

Final Summary Report

by A. D. Babinsky, R. G. Huebscher, R. J. Kiraly, T. P. O'Grady, and J. D. Powell

Prepared by
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Cleveland, Ohio
for Ames Research Center

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16. Abstract

NASA has developed an onboard aircrew oxygen generating system for tactical aircraft. Oxygen is generated by water electrolysis and carbon dioxide is removed from the rebreather loop by an electrochemical carbon dioxide concentrator.

This report includes a description of the water electrolysis and the CO_2 concentrator subsystems, a summary of the subsystem test results, a description of the integrated aircrew breathing system, and a summary of the preflight, flight, and post-flight test data. Other system and sub-system reports have been published and are referenced in this report.

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FOREWORD

The development work summarized herein, which was conducted by the Mechanical Products Division of TRW Inc., was performed under NASA Contract NAS2-4444. Details of the work performed are described in six separate technical reports as referenced in this report. The Contract Technical Monitor was P. D. Quattrone, Biotechnology Division, NASA Ames Research Center, Moffett Field, California.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

AIRCREW OXYGEN SYSTEM DEVELOPMENT
FINAL SUMMARY REPORT

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INTRODUCTION

Aircraft oxygen systems are currently limited to the use of stored supplies of oxygen in the form of liquid oxygen, high pressure gaseous oxygen, or solid state chemical oxygen. Use of oxygen from these sources limits the duration of a mission to the amount of stored gases and creates somewhat of a problem in logistics and service to provide the needed oxygen.

A means of avoiding these problems is the provision of a method of continuously generating oxygen on-board the aircraft as oxygen is required. This can be accomplished electrochemically by electrolysis of water or concentration of oxygen from the ambient air. The size and power requirements of these electrochemical oxygen generators would be large when coupled to an open loop aircraft oxygen system. If, however, a rebreather loop is provided such that the oxygen used corresponds to the pilot's metabolic consumption, the size of the oxygen generator and rebreather loop becomes competitive with a present-day LOX converter system.

The rebreather loop functions to recondition the exhaled gases such that it can be reused in the breathing cycle. The rebreather thus removes exhaled carbon dioxide, nitrogen, water vapor and heat.

Carbon dioxide can be removed by absorption in replaceable canisters by regenerative absorbers or by a continuous process electrochemical device. The regenerative absorbers are too big and complex for the intended application. Replaceable canisters re-introduce a minor logistics problem. The preferred mode of carbon dioxide removal is the continuous electrochemical process. Generation of oxygen by water electrolysis was selected to make the system independent of air source (high altitude or space application). The water will be added by refill of a water tank between missions. Ultimately, one can envision the recovery of water from the pilot's breath and the reaction products of the carbon dioxide concentrator and thus "close the loop" such that water refill requirements would be reduced.

Pacing items in the NASA Aircrew Oxygen System (NAOS) development were the TRW Static Water Feed Electrolysis Cell and the TRW Carbon Dioxide Concentrator. The Static Water Feed Electrolysis Cell, which operates independent of gravitational orientation, has evolved from TRW-sponsored programs and a NASA program for development of an orbital test electrolysis cell (Contract No. NASw-998).

The Carbon Dioxide Concentrator is a unique device which was initially developed by TRW. This electrochemical device separates carbon dioxide from air while producing electrical power. Hydrogen, which is required to operate the cell, is derived from the operation of the electrolysis cell.

Prior to the award of the NAOS Development Contract, NAS2-4444, life capability tests were performed on both the electrolysis cell and carbon dioxide concentrator using 3" x 3" test cells. Total operating time for the electrolysis cell, using static water feed, was over 3,000 hours while 9,150 hours were totaled on the TRW Carbon Dioxide Concentrator.

The basic objectives of the development program are summarized as follows:

- Design the system based on current technology and fabricate prototype model.
- Design, fabricate and test a laboratory model oxygen generating electrolysis module with static water feed, conduct feed water purity tests, and perform thermal analysis.
- Design, fabricate and test both single cell and full-scale laboratory model of a carbon dioxide concentrator, perform thermal analysis and develop improved version of concentrator module (Design II).
- Design, fabricate and test laboratory models of the system's power conversion and conditioning equipment.
- Design, fabricate or purchase and test breadboard models of the remaining system components.
- Design, fabricate and test a breadboard of the complete aircrew oxygen system using laboratory models of the components.
- Conduct long-term operating tests on the laboratory electrolysis module, the CO_2 concentrator single cells, and CO_2 concentrator laboratory module.
- Provide a Flight Breadboard System by redesign and use of Laboratory Breadboard System type components.
- Duplicate the hardware required to maintain the laboratory breadboard as a working system.
- Provide flight data acquisition equipment for monitoring and recording system parameters during flight testing.
- Provide equipment and associated spare parts necessary to convert C-131 aircraft electrical power into the resources needed by the FBS.
- Conduct flight test program, including pre-flight, flight and post-flight tests.

- Perform tests demonstrating the applicability of the major components of the Aircrew Oxygen System to low temperatures and high altitudes.

- Begin man-in-the-loop studies using the FBS.

- Conduct post-life test disassembly inspection of water electrolysis module and single cell CO_2 concentrators.

All the major hardware developed on the program is in use on other related government programs or plans are being made for the use of this equipment. All major objectives of the program were met. With the stable operation of the system noted under the wide variety of operating and storage conditions imposed, the system would appear to offer promise for use in other than aircraft applications. An example would be as oxygen supply and carbon dioxide removal devices for the space shuttle vehicle where ON-OFF type operation over varying mission durations and system capacities will be required.

WATER ELECTROLYSIS SUBSYSTEM[1]

Oxygen is produced in an electrolysis cell through the following electrode reactions:

$$\text{Cathode:}\quad 4H_2O + 4e^- \longrightarrow 4OH^- + 2H_2$$

$$\text{Anode:}\quad 4OH^- \longrightarrow 2H_2O + O_2 + 4e^-$$

A schematic of the basic electrolysis cell construction employed in the current oxygen generator is illustrated in Figure 1. The electrolyte is held in a porous matrix sandwiched between two catalytically active (platinized) electrodes. The water feed membrane maintains a separation of liquid electrolyte in the feed water cavity and gas in the hydrogen compartment during normal cell operation. Water diffuses from the feed membrane through the hydrogen cavity and electrode into the cell electrolyte to replace the water lost by electrolysis, and thus maintains the concentration of the cell electrolyte at a fixed value. Replenishment of the feed membrane water is provided by a static feed mechanism which incorporates an external water reservoir.

The Water Electrolysis Module (WEM) was designed as a laboratory type module utilizing air-cooled fins for heat removal and a static water feed system such that the module is capable of operation in all degrees of rotation. The physical characteristics of the cells and modules are summarized as follows:

Electrode Area:	33 in^2 (per cell)	No. Cells per Module:	10
Electrode Type:	AB-6	Module Size (overall):	7.75x11.0x4.39
Electrolyte Matrix:	Asbestos	Module Weight:	50 pounds
Cell Material:	Polysulfone	Module Voltage:	20 volts
Cell Size (overall):	7.75x11.0x0.36	Module Power:	460 watts
Current Density:	100 ASF	O_2 Generation Rate:	0.15 lb/hr

The individual cell structural components were machined from extruded polysulfone sheets. Endplates were machined of 3/8 inch thick stainless steel plate. Current collectors were formed by nickel plating copper sheets, followed by drilling and shearing to size after the plating operation. Electrodes, asbestos matrices and plastic screens were hand-cut to size. Module assembly was accomplished by stacking the individual components for ten cells on an assembly fixture. Insulated drawbolts, torqued in a predetermined pattern complete the module assembly. The completed module as used in the FBS is shown in Figure 2.

A test stand was designed and assembled to provide all the services, controls and instrumentation required for operation of the Water Electrolysis Module test plan including parametric, cyclic and extended life testing. Several modifications were made to increase the test rig reliability including removal of solenoid valves from shutdown circuitry, installation of a four-day capacity water feed tank and increased water capacity in condenser-filter trap assemblies.

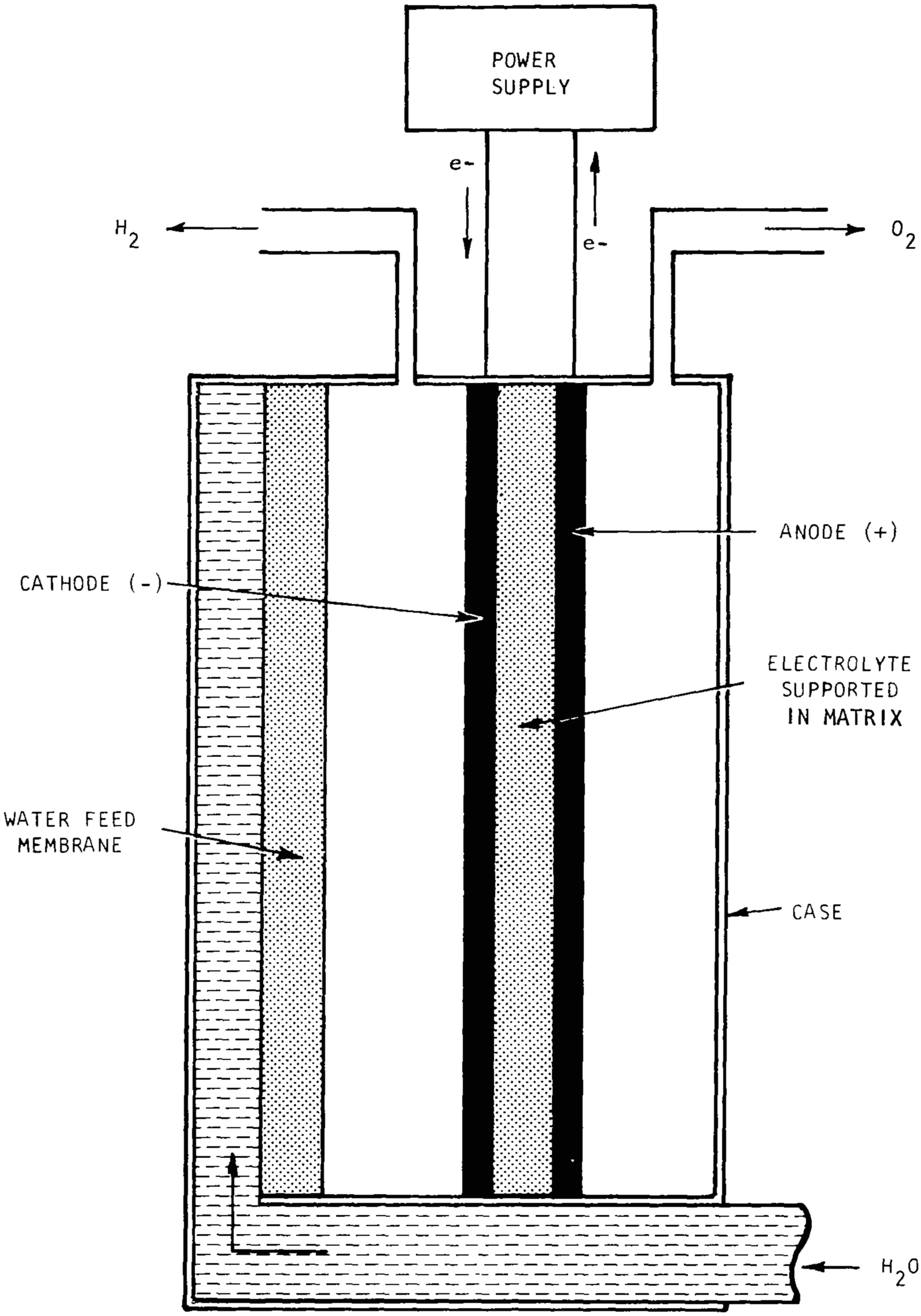


FIGURE 1 WATER ELECTROLYSIS CELL SCHEMATIC

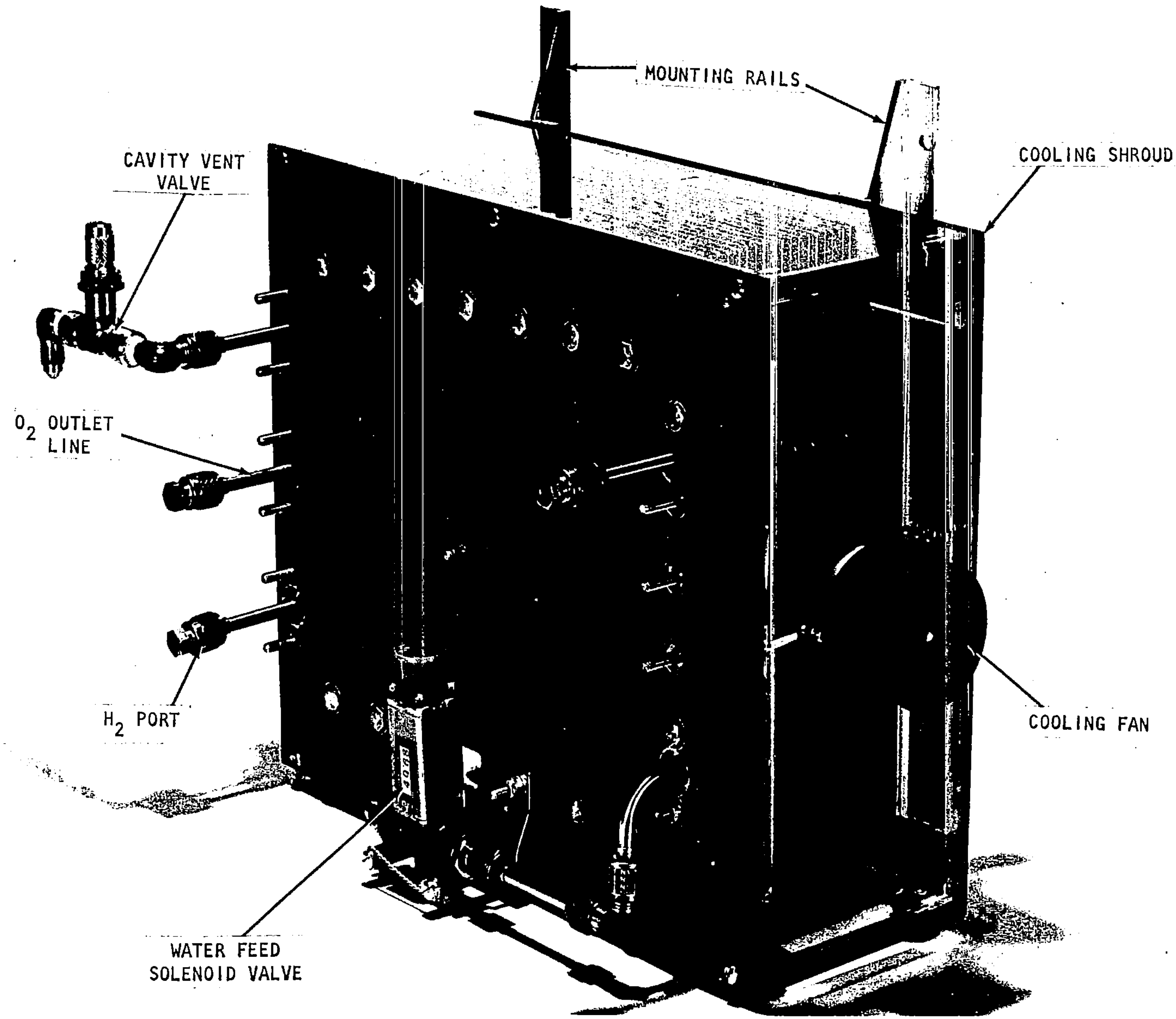


FIGURE 2 WATER ELECTROLYSIS MODULE

Parametric testing was accomplished to determine the performance of the module over a range of operating conditions including temperatures up to 182^{o}F, pressures up to 65 psig, and ±5.0 psi pressure differential across the cell matrix. Water balance studies were conducted over a 121-hour test period indicating a range of electrolyte concentrations of 0 to 13% KOH in the oxygen compartment and 22% KOH in the hydrogen cavity. Initial charge concentration was 25% KOH. Oxygen purity was shown to be over 99.5% by volume as measured by a Beckman E-2 Analyzer. Water feed tests demonstrated the applicability of the static feed concept using non-degassed water. Overcapacity was demonstrated by operation at 150 ASF for 8.5 hours. Typical polarization data, with cell operating at 175^{o}F and 67 psig, is as follows:

Current Density, Amps/Ft^2	Cell Voltage, Volts
25	1.58
50	1.64
75	1.67
100	1.71
125	1.73
150	1.76

Total parametric test time was 280 hours.

Module life testing consisted of cyclic tests to demonstrate short-term cold start operation and long-term tests to demonstrate long term operational stability and materials stability. The cyclic tests consisted of nineteen module startup-shutdown sequences with approximately ten hours of operation per run. Module operating conditions for these tests (total test time - 200 hours) were as follows:

Current Density, amps/ft^2	100
Stack Temperature, ^{o}F	174-185
O_2 Pressure, psig	50-67
O_2 to H_2 ΔP, psid	1.0-2.8
Stack Voltage, range, VDC	17.9-23.0
Cycle Duration, range, hrs.	5.3-10.2

Long-term life testing started in August 1968 at 480 hours module test time and continued through to December 1969 accumulating an additional 10,014 hours to yield a total test time of 10,494 hours. During the life of the module the assembly was exposed to electrolyte for a total of 13,607 hours. During the life test a number of shutdowns were encountered due to reasons as summarized:

No. of Shutdowns	Cause of Shutdown
11	Test rig service
32	Test rig malfunction
4	Operator error
6	Service interruption
5	Module malfunction
1	Module recharge

Module malfunctions consisted of two separate failures of water feed matrix support screens, two incidences of electrolyte leakage through epoxied access port plugs and one failure of cell matrix. The last failure occurred several days prior to scheduled shutdown. This failure of the cell matrix was the only such failure of WEM #1 during the entire test period of 10,494 hours spanning a period of 16 months.

Supporting tests and analyses were conducted as follows:

Thermal Analysis

A thermal design analysis was conducted to determine the most effective means of removing heat generated in the water electrolysis module due to cell inefficiencies. The cooling service limitations of the F-111 weapon system, which was the application considered for the NAOS System, were included in the study. Analysis of four heat removal methods considered applicable for aircraft use is contained in Appendix B of the Water Electrolysis Subsystem Report.[1] It was concluded that a single liquid cooling loop common to NAOS Subsystem would ultimately be employed in conjunction with liquid-to-air heat exchangers which would reject the heat to the aircraft's cooling media.

Water Feed Quality Test Program

An experimental study was performed to explore the possibility of employing an existing aircraft service fluid such as aircraft cooling water as a source of water for electrolysis instead of distilled water, thus decreasing aircraft maintenance requirements. The results of this study to establish the degree of effectiveness of aqueous glycol, aqueous methanol and tap water feed systems in a static water feed electrolysis system are described in Appendix A of the Water Electrolysis Subsystem Report.[1] The results indicate that an aqueous feed with an impurity level up to approximately 10% of the total feed can be tolerated and will function satisfactorily for limited time durations. Low vapor pressure contaminants reduce the possibility of contaminating the effluent oxygen stream.

Post-Test Disassembly Inspection

The results of a post-test disassembly inspection of the life test water module assembly (WEM #1) are summarized in Appendix C of the Water Electrolysis Subsystem Report.[1] A description of the condition of component parts of the assembly and photographs taken during disassembly of the module are included in the inspection report. Except for rather heavy corrosion of metal components in the oxygen cavities of the cell construction and permanent distortion of O-ring components, module components were in excellent condition after more than 10,000 hours of life test operation.

The major conclusions relative to the water electrolysis module development based on information derived from the NAOS development program are:

1. The long-term operational capability of the WEM as designed was demonstrated in the life test in which WEM #1 was operated for 10,494 hours.

2. The ability to maintain design performance capability for extended periods of continuous operation was demonstrated.

3. The module proved capable of immediate full operation after long storage periods in the charged (electrolyte) condition.

4. Additional study is required to establish more suitable materials for use in supporting the water feed matrix.

Based on NAOS program experience it is recommended that a Water Electrolysis Module Development Program should be continued, incorporating the following:

- Provision of a liquid-gas separator for degassing the feed water cavity

- Improved water feed matrix support

- Decrease the number of cell components and number of seals per cell

- Provide more integral structure for metal components to reduce electrical losses due to formation of metal oxides

- Improve sealing design

- Elimination of epoxied access ports

- More suitable selection of cell electrolyte concentration

- Selection of oxygen electrode more specifically designed for application

- Incorporation of internal liquid cooling passages

- Submodule construction to improve ease of assembly, check-out and repair

CARBON DIOXIDE CONCENTRATOR SUBSYSTEM[2]

Removal of carbon dioxide is accomplished by a TRW-developed electrochemical Carbon Dioxide Concentrating Module (CDCM). The module consists of cells in which two porous electrodes are separated by an asbestos capillary matrix containing an aqueous solution of an alkali metal carbonate. Cell plates adjacent to the electrodes provide passageways for distributing the gaseous reactants over the surface of the electrodes.

The simplified chemical and electrochemical reactions occurring in a cell of the module are shown in Figure 3.

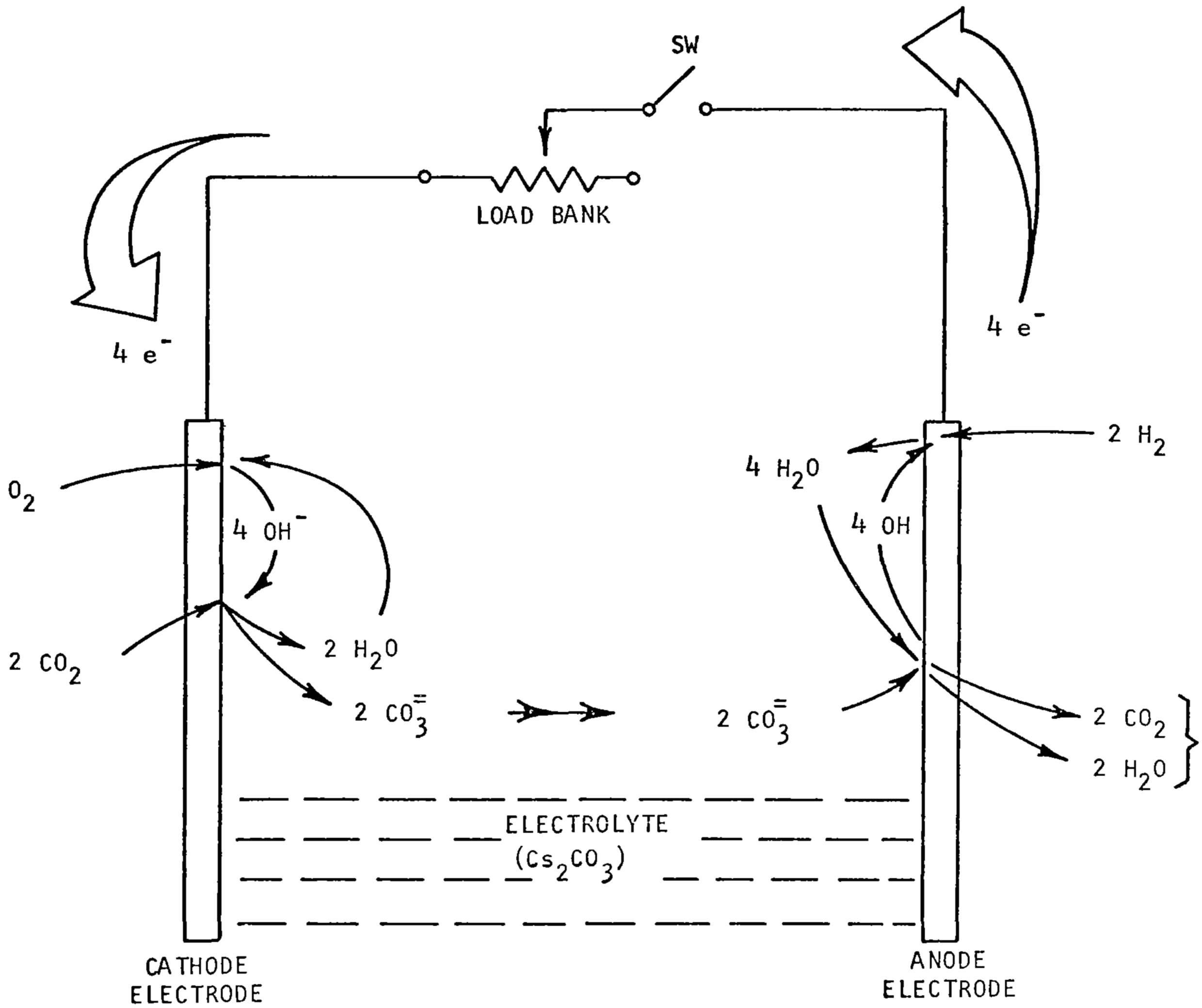
The reaction of oxygen and water forms hydroxyl ions (OH^-), a well-known "getter" of carbon dioxide (for example, LiOH). Any carbon dioxide which passes over the electrolyte, now rich in hydroxyl ions, reacts to form carbonate ions ($CO_3^=$). At the opposite electrode (anode) the reaction of hydrogen and hydroxyl ions to form water causes the electrolyte to be deficient in hydroxyl ions. Thus, carbon dioxide is given off, completing the transfer of carbon dioxide from the oxygen atmosphere to the hydrogen atmosphere. Hydrogen is available to the module as a waste product from the water electrolysis module, thereby permitting the concentrator to be operated in the hydrogen depolarized mode. In this mode of operation, the unit generates power much as a fuel cell and has the capability of supplying electrical power to other portions of the NAOS system if desired.

This system is completely static, the only moving parts being in the subsystems which service the concentrator cells. The system readily lends itself to zero gravity operation since mass transfer occurs only in the gaseous state. There are no free liquids or components dependent upon gravity operation.

At the start of the program, available data covered narrow operating ranges for small single cells. Thus,pparametric testing of single cells was conducted to provide the necessary data to design a specific full-scale carbon dioxide concentrator.

Four small cells utilizing differing materials of construction, and internal cell geometry were fabricated. A parametric test rig and a three-cell, life test rig were designed and fabricated for the single cell effort. The parametric test rig was used to determine the performance of the cells over a wide range of conditions. The instrumentation utilized in the parametric test stand was more accurate and complete than that used on the life stands in which all three cells were run at the same conditions of gas flow, pressure and dew point. Separate current loading systems were provided for the cells, thus allowing each unit to be run at a different current density. Parametric tests were conducted to characterize cell performance as a function of reactant pressure, oxygen, carbon dioxide and hydrogen flow rate, cell temperature, and current density.

Two cells utilizing nickel endplates were run on life test. One of these units was run for 13,071 hours and the other for 11,684 hours. Additional cells tested on the life test rig comprised two units with polysulfone endplates, one unit with titanium endplates and two units of module configuration. The



$O_2 + 2\ H_2O + 4\ e^- \longrightarrow 4\ OH^-$ (ELECTRODE)

$2\ CO_2 + 4\ OH^- \longrightarrow 2\ CO_3^= + 2\ H_2O$

(CATHOLYTE)

$H_2 + 4\ OH^- \longrightarrow 4\ H_2O + 4\ e^-$ (ELECTRODE)

$2\ CO_3^= + 2\ H_2O \longrightarrow 2\ CO_2 + 4\ OH^-$

(ANOLYTE)

OVERALL REACTION:

$$O_2 + 2\ CO_2 + 2\ H_2 \longrightarrow 2\ CO_2 + 2\ H_2O + \text{ELECTRICAL ENERGY} + \text{HEAT}$$

FIGURE 3 SCHEMATIC REPRESENTATION OF CARBON DIOXIDE CONCENTRATOR CELL purpose of these tests was to obtain data on the compatibility of cell materials when exposed to normal carbon dioxide concentrator cell operating environments. After completion of these tests, the units were torn down and examined for evidence of corrosion. Very little change in appearance of cell components prior to and after the test was noted.

The Carbon Dioxide Concentrator Module (CDCM) was designed as a laboratory test module utilizing air-cooled fins for heat removal and the matrix type of construction referenced above that permits operation of the module in any attitude, The physical characteristics of the first unit, referred to as CDCM I, are summarized as follows:

Electrode Area:	35 in^2 (per cell)
Electrode Type:	AB-6
Electrolyte Matrix:	Asbestos
Electrolyte:	Potassium Carbonate
Cell Material:	Machined polysulfone
Gas Cavity Spacer:	Expanded silver
Heat Removal Plates (current collectors):	Silver
Seals:	Ethylene propylene O-rings
Cell Size (overall):	7.5 x 13.8 x 0.17
Current Density (max.):	40 ASF
No. of Cells per Module:	10
Module Size (overall):	7.5 x 13.8 x 3.2
CO_2 Transfer Rate:	0.117 lb/hr
CO_2 Partial Pressure:	3.8mm Hg

The individual cell, structural components were machined from extruded polysulfone sheet. Endplates were machined of 5/16" thick stainless steel plate. Current collectors were fabricated by stack milling silver sheet stock. Gas cavity spacer material was fabricated from expanded silver sheet. Electrodes and asbestos matrices and frames were hand-cut to size. Module assembly was accomplished by stacking the individual components for ten cells on an assembly fixture. Insulated drawbolts, torqued in a pre-determined pattern completed the assembly.

A test stand was designed and assembled to provide all the services, controls and instrumentation required for operation of the carbon dioxide concentrator module in accordance with the test plan. This plan included parametric, cyclic and extended life tests. The test system is equipped with an oxygen recycle and oxygen/carbon dioxide feed system to typify the operation of the module when part of the Rebreather System. With this test system, the operator has the capability of controlling and monitoring the module current, average cell temperature, dew point temperature of both oxygen and hydrogen entering the module, carbon dioxide flow rate into the recycle loop, the oxygen recycle rate through the loop, the hydrogen rate into the module, the total gas pressures on the oxygen and hydrogen sides, and the partial pressure of the oxygen on the recycle side. For the various ranges of the above-mentioned independent parameters, the operator can observe the following dependent parameters: individual cell voltages, module voltage, carbon dioxide concentration in the effluent oxygen and hydrogen streams, and the oxygen consumption of the module. Test points were provided to check the performance of the gas analyzers within the test system as well as to obtain a more complete survey of the carbon dioxide concentrations and other gas components with a Beckman GC-2 Gas Chromatograph. Internal cell iR drop and cell iR-free voltages can be determined with the aid of an interrupter circuit built into the test stand.

The parametric test series was designed to provide operating data for the carbon dioxide concentrator module as a function of the following: cell temperature, oxygen circulation rate, hydrogen flow rate, current density, and carbon dioxide transfer rate.

During the course of the parametric test series it became apparent that a uniform distribution of hydrogen to the ten cells was not being achieved. Consequently, the internal manifolding of the hydrogen stream was changed from a parallel to a series flow configuration. In the modified flow system, the first cell in the series configuration receives pure hydrogen and the last cell in the stack receives approximately 70 percent hydrogen and 30 percent carbon dioxide. Stable performance was obtained using this flow pattern with the ten-cell module tested. Subsequent parametric tests disclosed that the unit could transfer carbon dioxide at the design rate of 0.45 slpm at a current of 10 amperes while maintaining the carbon dioxide level at the oxygen exit end of the stack below 0.3 percent.

This determination was made with a hydrogen flow rate of 1.7 slpm, an oxygen recycle rate of 2.7 SCFM and a stack temperature in the range of 117-130°F. The electrolyte used in these tests was 30 w/w% K_2CO_3 solution.

After completion of the parametric test series, life tests were conducted with the module. Moisture balance difficulties in long term operation led to the design and fabrication of CDCM II. Prior to initiation of the redesign, an analysis was made of alternate means of removing heat and moisture from the unit. The analysis included the original fin-cooled unit as well as a unit employing static water feed to provide both increased water tolerance, gas humidity conditioning and evaporative cooling, and a unit utilizing a circulating electrolyte. Consideration of the advantages, disadvantages and requirements of the above concepts for CDCM II led to the conclusion that a redesigned, fin-cooled concentrator module using an alternate electrolyte would best meet all the objectives.

The design objectives for the second unit were: increased carbon dioxide transfer capability (100% overcapacity); elimination of any possibility of corrosion; elimination of excessive internal temperature gradients; utilization of a superior electrolyte to provide increased performance and water tolerance; improved sealing; decreased pressure drops; utilization of methods of construction amenable to mass production; and utilization of materials that would permit operation in the carbonation (non-depolarized) mode.

During the carefully controlled tests, possible with the NAOS-developed equipment, it was disclosed that bicarbonate formation and precipitation was occurring. The precipitate accumulated within the anode and masked this electrode from the gas phase, seriously reducing performance. In addition, gas ports on the hydrogen side of the cell were blocked.

A survey of all of the alkali metal carbonates and bicarbonates with respect to solubility limits and vapor pressure depression was initiated. A study was made to determine the criteria for electrolyte selection from which candidate alkali metal carbonates could be selected. Some of the required property data for this selection was available in the literature and some was determined by test during the program. From this analysis cesium carbonate emerged as the preferred electrolyte although rubidium carbonate very likely could also be utilized. Virtually no property data was available on the latter.

From a review of the materials examined in the Carbonation Cell Materials Compatibility study, NASA CR-1481, titanium was selected as the most desirable metallic material and ethylene propylene rubber was selected for the sealing material. Knowing the thermal conductance of all cell components as well as property data for aqueous solutions of cesium carbonate (such as solution volume and vapor pressure data) the water tolernace of the unit was maximized. The physical characteristics of the redesigned concentrator, CDCM II, are summarized in the following:

Electrode Area:	35 in^2 (per cell)
Electrode Type:	AB-6
Electrolyte Matrix:	Asbestos
Electrolyte:	Cs_2CO_3
Cell Material:	Injection molded polysulfone
Gas Cavity Spacer:	Expanded titanium
Heat Removal Plates (current collectors):	Titanium clad copper
Seals:	Flat, ethylene-propylene gaskets
Cell Size (overall):	7.7 x 13.7 x 0.15
Current Density (max.):	40 ASF
No. of Cells per Module:	15
Module Size (overall):	7.7 x 13.7 x 4.5
CO_2 Transfer Rate:	0.234 lb/hr
CO_2 Partial Pressure:	3.8mm Hg

Polysulfone plastic was utilized for the cell housing parts. These were injection molded in an aluminum mold using an eight ounce molding machine. Endplates were machined from 5/16" thick stainless steel plate. Current collectors were fabricated by die cutting copper sheet stock. Titanium clads were die cut and adhesively bonded to both sides of the copper sheet. The titanium sheets were welded to each other in the region of through manifold holes. Gas cavity spacer material was fabricated from expanded titanium sheet. The flat gaskets were die cut from EPR. Electrodes and asbestos matrices were hand-cut to size. Module assembly was accomplished by stacking the individual components for fifteen cells on an assembly fixture. Insulated drawbolts, equipped with spring washers, were torqued in a pre-determined pattern to complete the assembly. A comparison of the components of the original and the re-designed modules are shown in Figure 4.

The test stand was modified to provide a fifteen-cell capability. In addition, the oxygen dehumidifier was replaced by a device that would permit both humidification and dehumidification. The oxygen recycle loop was equipped with a flowmeter and was trace-heated. The flow capability of the stand was increased in accordance with the 100% overcapacity requirement for CDCM II.

A four-cell module was assembled to conduct a design verification test. This unit was run for 76 hours in the hydrogen depolarized mode at which time the hydrogen source was valved off. The unit was then run in the powered mode for 62 hours. The module was then disassembled and tear-down observations made. The fifteen-cell module shown in Figure 5 was assembled for the parametric test series. Performance was obtained as a function of the ratio of carbon dioxide transfer rate to current, stack temperature, pCO_2 at the cathode (with N_2 as diluent), hydrogen feed rate, and oxygen recycle rate. The parametric tests disclosed that the unit could transfer carbon dioxide at the design rate of 0.45 slpm at a current of 5 amperes while maintaining the carbon dioxide level at the oxygen exit end of the stack below 0.3%. At the 100% overload condition (at a stack current of 10 amperes) the carbon dioxide level at the oxygen exit of the stack was approximately 0.2%. These data were taken with a hydrogen flow rate of 1.7 slpm, an oxygen recycle rate of approximately 3.6 SCFM and a stack temperature of 110°F. The electrolyte used in these tests was 55 w/w% Cs_2CO_3 solution.

An increase in stack temperature markedly increased stack voltage, however, the carbon dioxide level in the rebreather loop increased slightly. Stack voltage decreased slightly at a pO_2 of 3 psia and the unit functioned stably at a pO_2 of 1.1 psia. When hydrogen feed rate was reduced to a value near stoichiometric, the carbon dioxide level in the hydrogen leaving the unit was in the order of 90 percent. The voltage of the last cell in the stack was still acceptable. The test data showed that increased oxygen recycle rate decreased the carbon dioxide level in the rebreather loop with all other conditions constant. After completion of the parametric test series, a life test was conducted upon the 15-cell module. A total of 1,845 continuous load hours were logged on the second module with 509 hours of this as parametric test time. A total of 169 hours were logged on the predecessor module that was damaged during a test rig malfunction. No electrolyte recharges were necessary to sustain the operation of either unit during the test effort. The life test on the second unit was terminated by completion of contract requirement.

The major conclusions relative to the carbon dioxide concentrator module assembly based on information derived from the NAOS development program are:

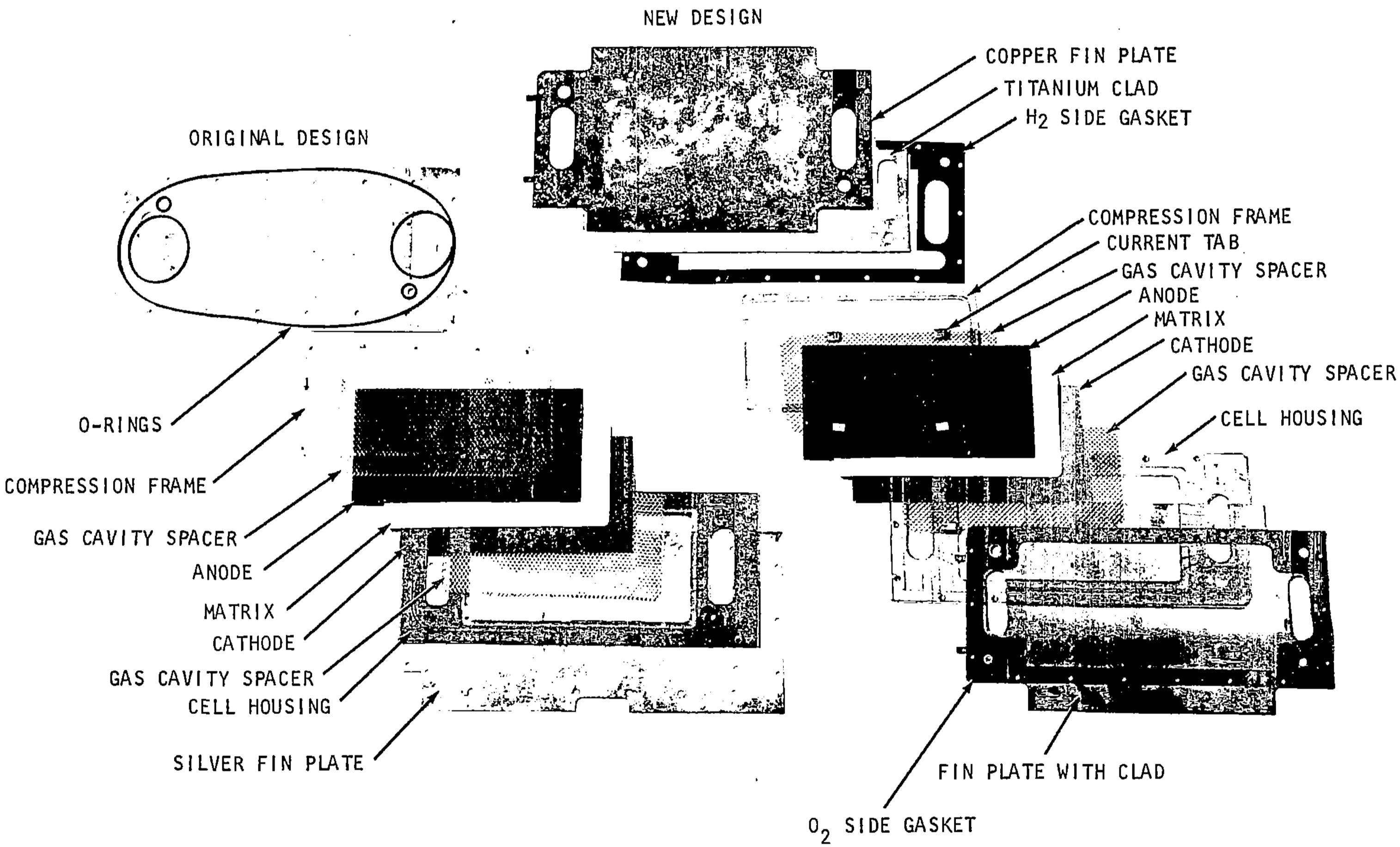


FIGURE 4 CARBON DIOXIDE CONCENTRATOR MODULE COMPONENTS

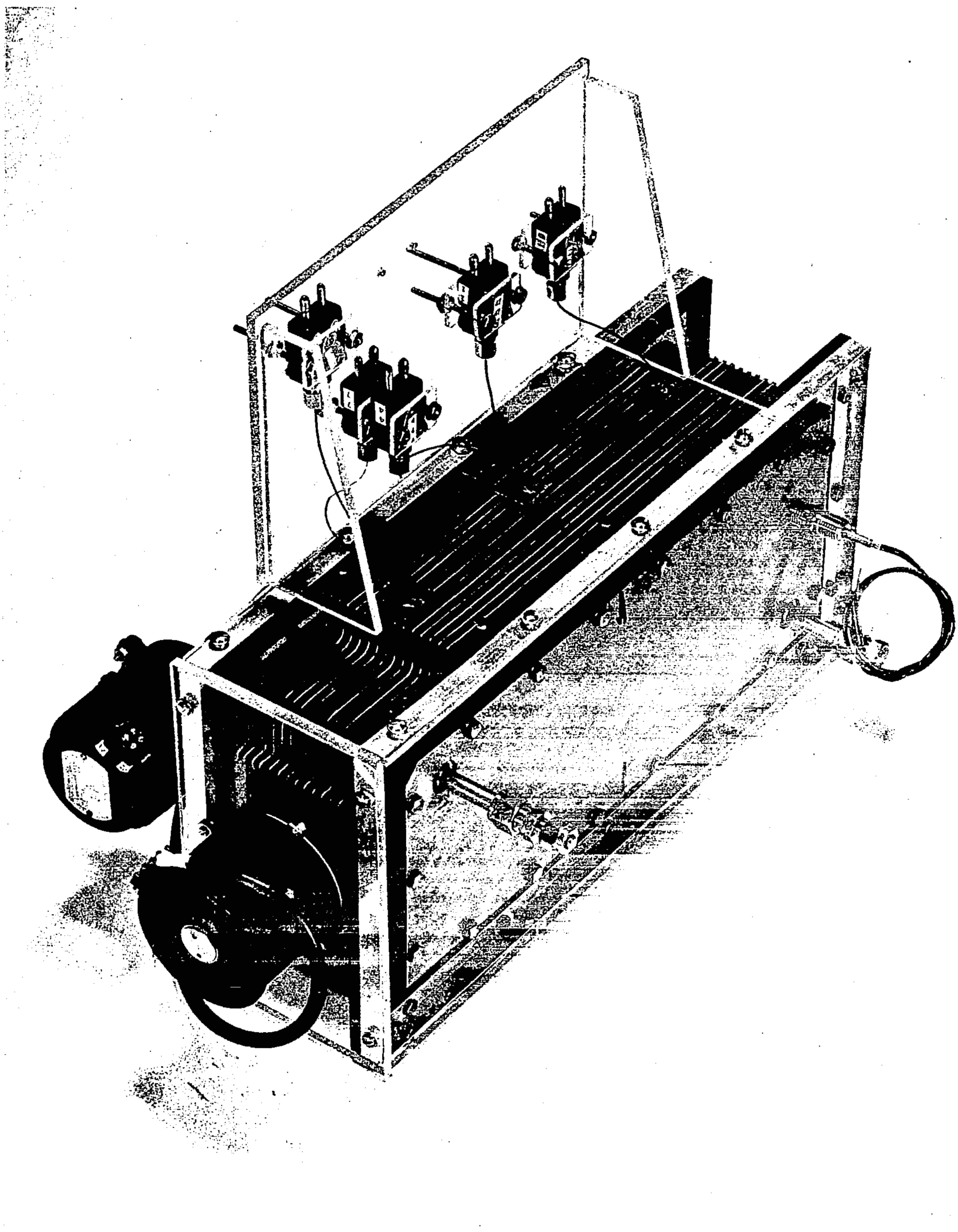


FIGURE 5 15-CELL MODULE WITH SHROUD AND BLOWERS

1. Silver is not a suitable material for long-term module operation over the complete range of operation from full load to open circuit conditions.

2. Potassium carbonate solution is not a suitable electrolyte for stable operation.

3. Long-term operation of carbon dioxide concentrator cells and modules is feasible using cesium carbonate electrolyte.

4. The titanium clad copper assembly is suitable for use as a bipoler plate in the carbon dioxide concentrator.

5. The carbon dioxide concentrator module meets the system design requirements for carbon dioxide removal, using the series hydrogen flow pattern.

6. The carbon dioxide concentrator module is capable of maintaining carbon dioxide partial pressures below 1mm Hg in the closed loop system.

7. The ability of the concentrator module to maintain design performance capability for extended periods of continuous operation was successfully demonstrated.

8. Operation of the module in an ON-OFF cycle characteristic of short-term aircraft operation is entirely satisfactory.

9. Full operation after long storage periods is possible.

Based on NAOS program experience, it is recommended that a carbon dioxide module development program should be continued, incorporating the following:

1. Perform investigation necessary to provide additional data on methods which can be used to increase the specific transfer rate of carbon dioxide at low carbon dioxide partial pressures.

2. Module development should be continued with the objective of developing an efficient carbon dioxide concentrator for use in either aircraft or spacecraft life support systems.

LABORATORY BREADBOARD SYSTEM[3]

The system design in this phase consisted of two separate designs: 1) the laboratory breadboard system and 2) a preliminary design of a fully-developed prototype.

The design objectives for NAOS (NASA Aircrew Oxygen System) were to obtain a safe, reliable system of low weight and size which would eliminate the need for ground support facilities and minimize the time and effort for maintenance. The Laboratory Breadboard System (LBS) was the feasibility model of this system composed of laboratory type components. The system design specifications were based on the physiological requirements of a pilot. The breathing loop preliminary design requirements are outlined in Table I which also shows the basis for the requirements. These requirements were revised and expanded in later phases of the NAOS development. The basic system concept description is deferred to the Flight Breadboard System section for purposes of this report.

Design of the fully-developed system was completed using the F-111 aircraft specifications for flight profile and on-board services as a design guide. Completion of this design indicated the importance of working directly with the aircraft designer to achieve a proper integration of the oxygen system with the aircraft system. A mock-up of the prototype is shown in Figure 6. The system would have an oxygen generating capacity of 0.20 lb/hr, weight of less than 50 pounds, volume of less than one cubic foot and consume less than 700 watts power.

A comparison of the size and weight of some of the major system components for the LBS hardware and the projected prototype are given below.

	Size, inches		Weight, pounds	
Component	Present	Prototype	Present	Prototype
Electrolysis Module	4.4x8x11	3x6x8	51	16
CO_2 Concentrator	5x7x13	8x7x2	36	10
Water Reservoir	6 dia. x 5.4	4.1 dia. x 5	5 (filled)	3.5 (filled)
Electrolysis Module Power Control	7x5x9x10	5x6x4.5	6.1	2.5
CO_2 Concentrator Load Control	5x6.3x8.5	4x2.5x2	3	1.5

Development of the water electrolysis and carbon dioxide concentrator subsystems were accomplished under separate tasks. The electrical control subsystem, the rebreather subsystem and related components were developed under the laboratory breadboard system task.

Power conditioning and controls development included the water electrolysis and carbon dioxide concentrator rate controls, recirculation loop blower speed control and the module temperature controls.

TABLE I

BREATHING LOOP DESIGN REQUIREMENTS

	Requirement	Basis for Requirement
1.	Pilot's oxygen consumption - 0.10 lb/hr	Based on data for light work typical of piloting aircraft
2.	Electrolysis cell oxygen flow rate - 0.15 lb/hr	Pilot's consumption plus 0.05 lb/hr for CO_2 concentrator consumption
3.	Pilot's respiratory minute volume - 0.5 CFM (14 liters/min)	Typical for light work, also actual measurements on pilots
4.	Peak instantaneous respiratory flow rate - 1.6 CFM	Assumes sinusoidal respiratory flow
5.	Pilot's tidal volume - 0.78 liters	Based on tests, varies with individuals
6.	Temperature of breathing oxygen to pilot - 60°F to 90°F (70°F - 80°F preferable)	Comfort
7.	Relative humidity of breathing oxygen to pilot - 50% maximum	Comfort
8.	Breathing loop absolute pressure levels 3 psia to 15 psia	Sea level to physiological minimum safe pressure
9.	CO_2 concentration in breathing oxygen to pilot - 1% by volume maximum at one atmosphere (7.6mm Hg vapor pressure maximum)	Well under safe maximum
10.	CO_2 production by pilot - 0.12 lb/hr nominal	Metabolically consistent with oxygen consumption
11.	Operating duration - 10 hours	Typical oxygen capacity of existing systems

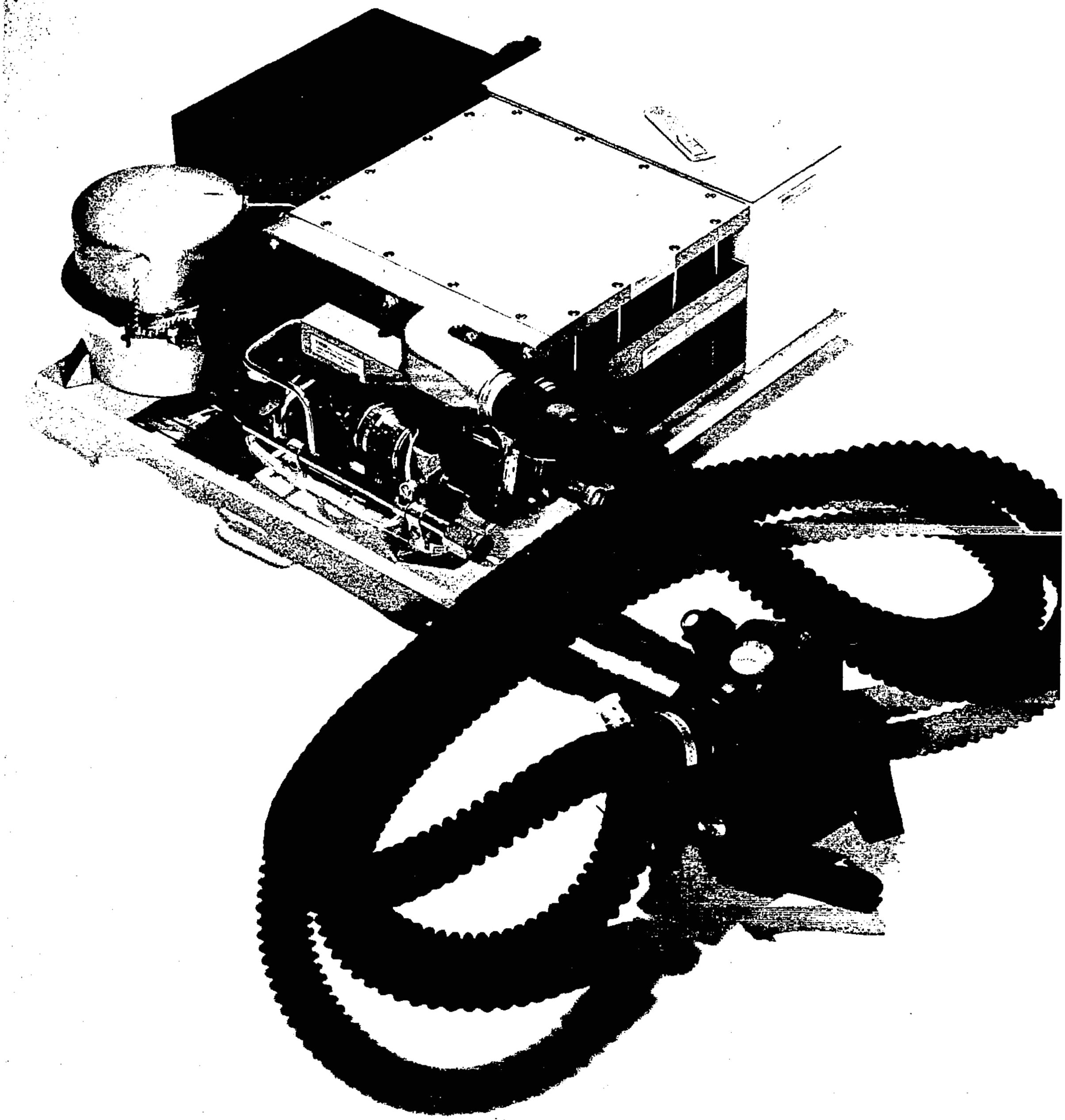


FIGURE 6 NAOS PROTOTYPE MOCK-UP WITH BREATHING MASK

The water electrolysis rate control consisted of a current regulator operating in a pulse width modulation switching mode at a frequency of 5K Hz. Control of switching rate varies the current to the module. Input to the switch control is either by manual setting of a potentiometer or the automatic mode with input from a pressure transducer. Efficiency of the current control device in this configuration was 86 percent.

Control of the carbon dioxide module carbon dioxide transfer rate is accomplished by control of the load current through the module and a load transistor. A control circuit with a manual setting of a potentiometer is used to set the current flow through the load transistor.

System accessories are defined as those items not specifically in the electrochemical component subsystems or the power conditioning and controls. The accessory components are the remaining components in the rebreather loop such as the counter-lung and pressure control, the recirculating loop blower, heat exchangers, and the hydrogen elimination device. The accessories are required to meet performance but are not necessarily flight size or weight. Standard off-the-shelf components were employed wherever possible for use in the laboratory breadboard system.

The counter-lung/pressure control is the major accessory component. The counter-lung, a flexible bag within a rigid container, functions as a volumetric gas reservoir to accommodate the variation in the breathing loop gas volume as the aviator inhales and exhales. Pressure control components maintain the pressure in the container equal to the rebreather loop pressure, including safety pressure and a high altitude pressure breathing schedule. This assembly is shown under test in Figure 7.

Prior to completing the entire integrated laboratory breadboard system, the water electrolysis and carbon dioxide concentrator subsystems were available. To provide additional operating data on these two subsystems, endurance tests were conducted. Operating time on the water electrolysis module was 1,562 hours while 528 hours on load were accumulated on the carbon dioxide concentrator module while operating at normal design conditions.

Following the endurance tests the accessory components were integrated with the water electrolysis and carbon dioxide concentrator subsystems into the configuration shown in the system schematic, Figure 8. The Laboratory Breadboard System is shown in Figure 9 with the Design II carbon dioxide concentrator installed. The LBS test program was conducted with the Design I carbon dioxide concentrator.

Operation of the complete LBS was the first operation of an aircrew oxygen system using electrochemical oxygen generation and carbon dioxide removal. Feasibility was definitely established demonstrating that a prototype system could be developed.

Test operations conducted included start-up tests, steady state operation under varying breathing rates and volumes, and off-design operation. Off-design operation included operation without the recirculation blower. Performance in

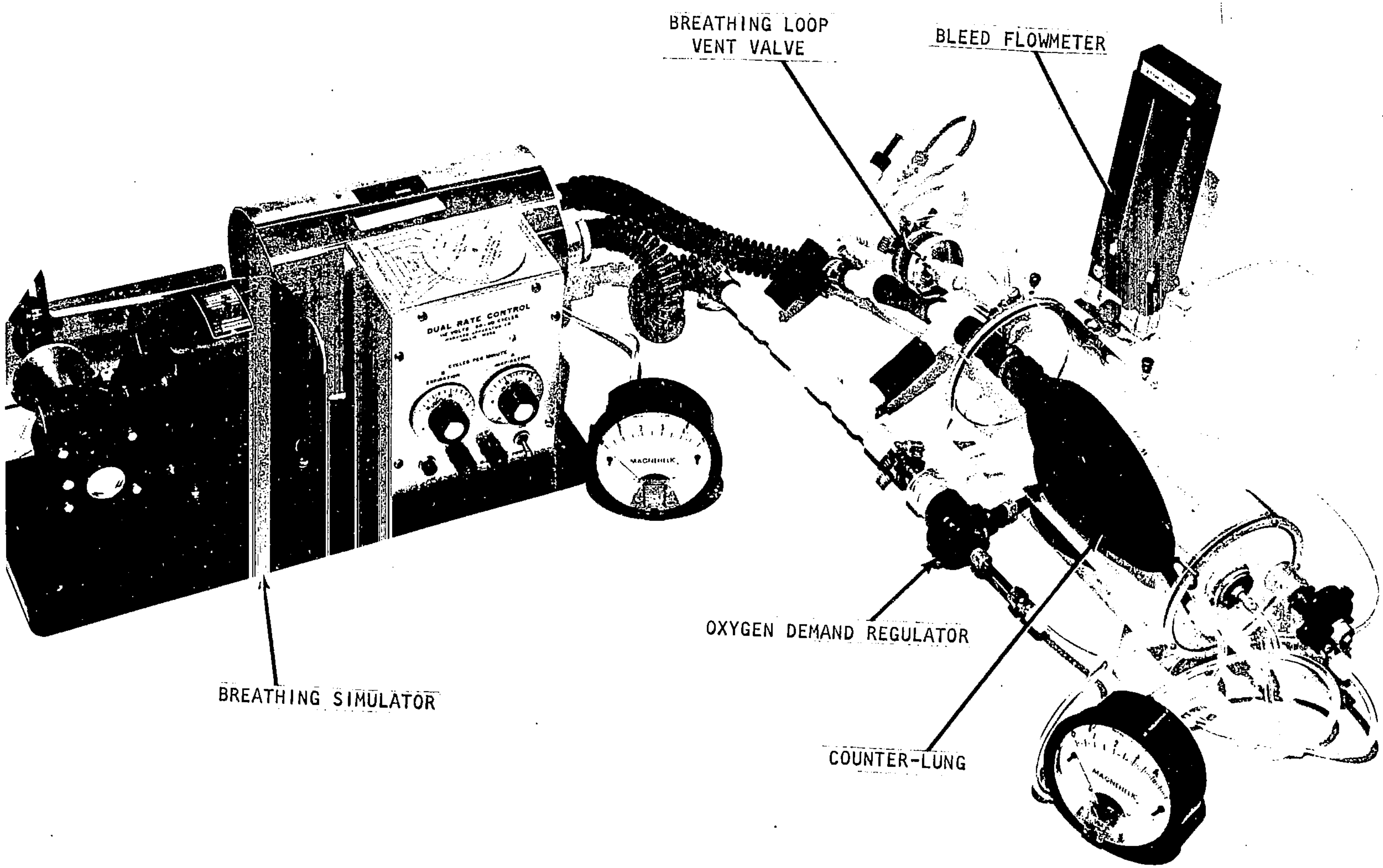


FIGURE 7 BREATHING LOOP TEST SET-UP

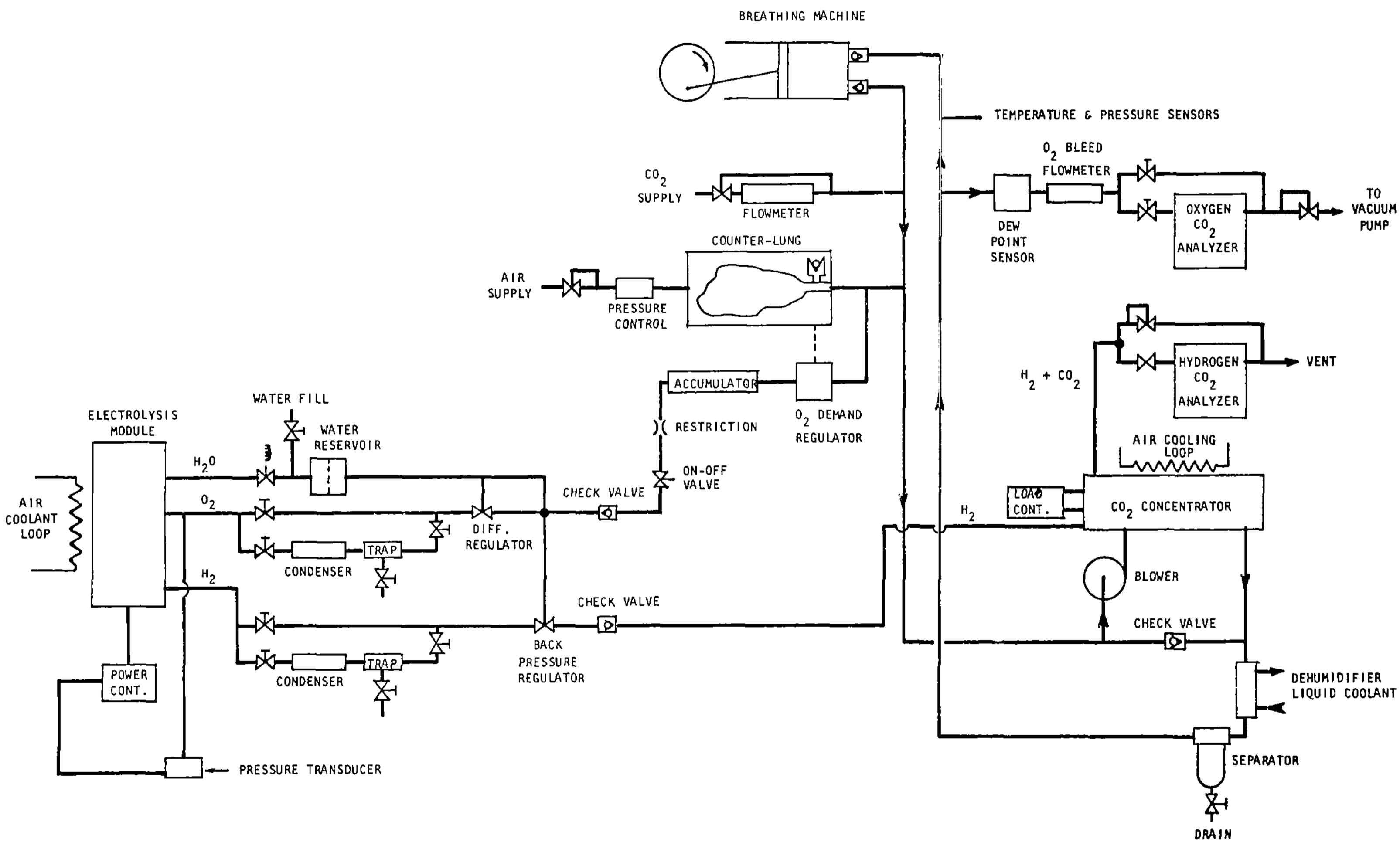


FIGURE 8 NAOS - LABORATORY BREADBOARD SYSTEM SCHEMATIC

FIGURE 9 NAOS LABORATORY BREADBOARD SYSTEM

this mode indicated system performance can be maintained with only pilot breathing used to provide gas flow through the carbon dioxide concentrator. Table II presents normal LBS operating conditions.

Following the normal test series, the water electrolysis module and the power conditioner were modified to provide a 50 ampere capacity to increase the oxygen generation rate capacity up to 0.33 pounds per hour. Following the modification, the system was operated in the "open loop" mode by feeding the oxygen supply into a diluter demand regulator as a feed to the pilot's mask. Feasibility and versatility of the system was further demonstrated by this test.

TABLE II

NAOS LABORATORY BREADBOARD
OPERATING CONDITIONS

O_2 Generation Rate		0.15 lb/hr
O_2 Generation Pressure		73 psia
CO_2 Concentrator Current		7.6 amps
Breathing Simulation:		
	Respiration Rate	10-30 cycles/min
	Tidal Volume	0.5-1.0 liter
	O_2 Bleed	0.10 lb/hr
	CO_2 Inflow	0.117 lb/hr
Breathing Gas Delivered at:		
	Temperature	$70^{\circ}F-80^{\circ}F$
	Relative Humidity	40%-60%
	Total Pressure	1 atm.
	CO_2 Partial Pressure	2.0-7.6mm Hg
Operating Time		105.4 hrs
Number of Start-Ups		29
Longest Continuous Run		8.2 hrs

FLIGHT BREADBOARD SYSTEM[5]

System Description

The Flight Breadboard system (FBS) is the first packaging of the laboratory type components into a complete oxygen system allowing operation outside of the laboratory. Figure 10 is a photograph of the FBS. The prime consideration used in packaging the system is maximum component accessibility with secondary emphasis on minimizing package volume. No auxiliary equipment was located within the system package. The FBS is mounted in a tubular, aluminum frame, 26" wide, 25" deep and 25" high. The Aircrew Oxygen System as shown in Figure 11 (Flight Breadboard System Schematic) consists of four primary subsystems: 1) Water Electrolysis, 2) Carbon Dioxide Concentrator, 3) Rebreather and 4) Electrical Control.

Hydrogen and oxygen gases are generated in the Water Electrolysis Subsystem at 75 psia. Oxygen gas is fed to the rebreather loop through the oxygen demand regulator. A blower in the rebreather loop circulates the oxygen gas through the carbon dioxide concentrator. The hydrogen gas from the electrolysis module is fed to the carbon dioxide concentrator where it reacts electrochemically with oxygen to remove carbon dioxide from the rebreather loop. The carbon dioxide is vented with excess hydrogen.

The pilot's exhalation enters the counter-lung which accommodates the pilot's tidal volume during breathing to maintain the loop at constant pressure during the breathing cycle. Inhalation oxygen is drawn from the circulating loop through a heat exchanger used as a dehumidifier.

The Electrical Control Subsystem (ECS) provides power conditioning, oxygen generation rate control, carbon dioxide removal rate control, component temperature control, safety indicators and shutdown circuitry, system status readouts and fault isolation circuitry. A major portion of the ECS circuitry was developed specifically for the FBS. The ECS is shown in Figure 12.

System performance characteristics are given by reference to the detailed component specifications presented in Table III.

In addition to the FBS, four other packages were used in the testing. These were: 1) a breathing simulator to produce respiration flow rates and oxygen consumption and carbon dioxide addition at metabolic rates; 2) a resources adapter to provide coolant and compressed air services to the system which were unavailable on the C-131F aircraft; 3) an instrumentation package providing visual readouts of the system and component operating parameters; and 4) a tape recorder to record the important data.

Flight Test Program[4]

The purpose of the Flight Test Program was to demonstrate operation of an integrated system away from a laboratory environment; provide first packaging experience; provide experience in working with potential user agency; identify aircraft system interface problems; identify effects of flight environment upon

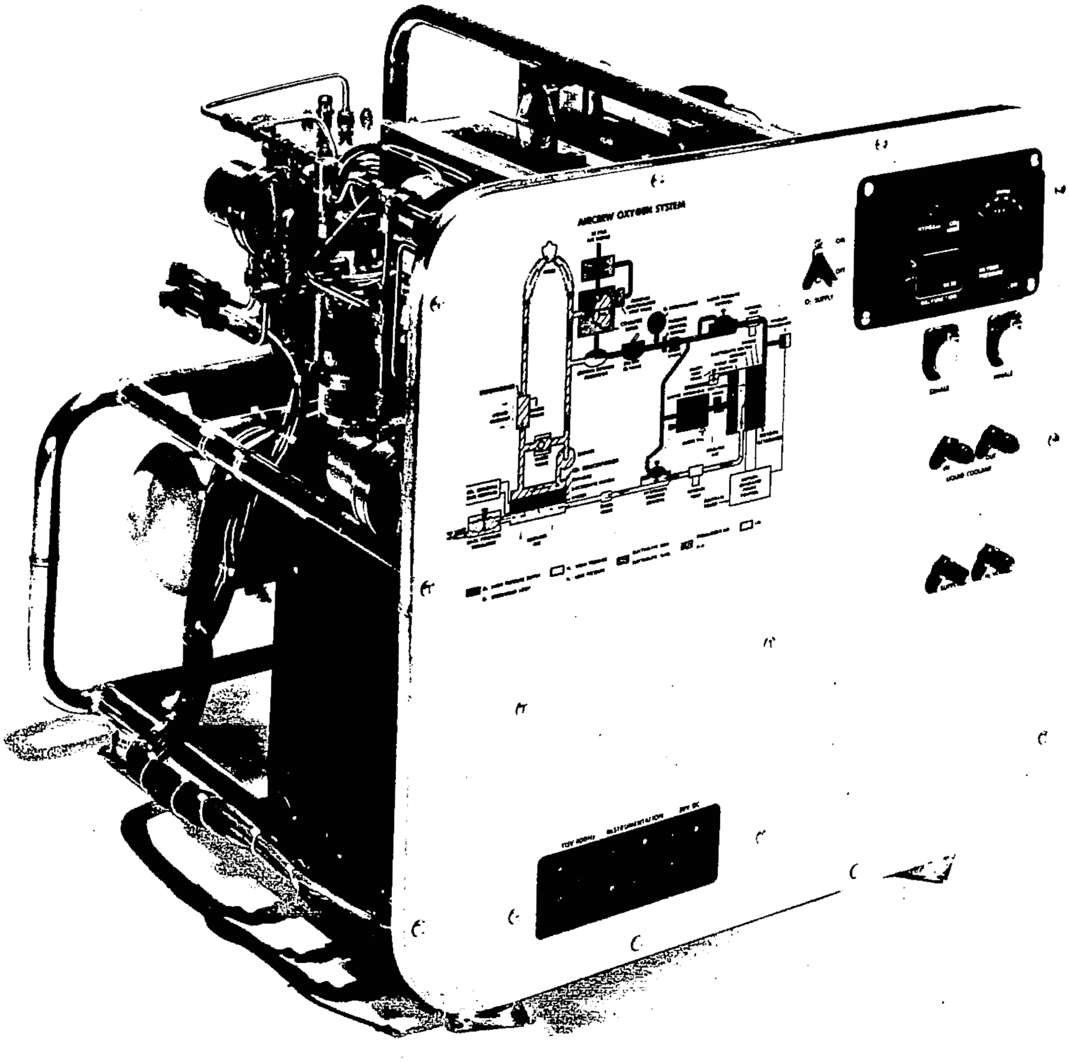
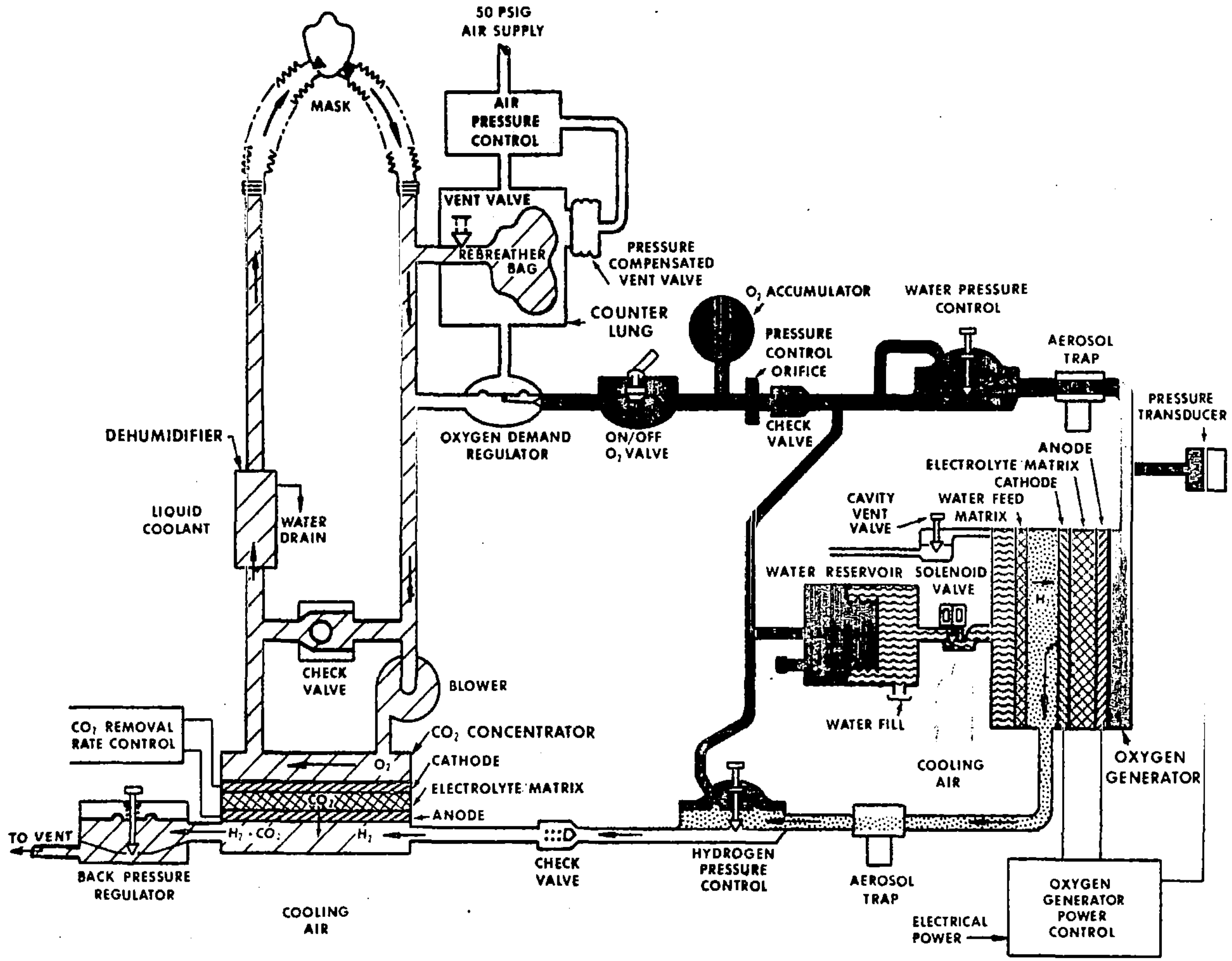


FIGURE 10 FLIGHT BREADBOARD SYSTEM



O_2 - HIGH PRESSURE SUPPLY / O_2 - REBREATHER LOOP

H_2 - HIGH PRESSURE / H_2 - LOW PRESSURE

ELECTROLYTE KOH / ELECTROLYTE Cs_2CO_3

PRESSURIZED AIR / H_2O

CO_2

FIGURE 11 AIRCREW OXYGEN FLIGHT BREADBOARD SYSTEM SCHEMATIC

FIGURE 12 ELECTRICAL CONTROL SUBSYSTEM PACKAGE

TABLE III

COMPONENT PERFORMANCE SPECIFICATIONS

Electrolysis Module Assembly	
Oxygen Generation Rate:	0.15 lb/hr, nominal 0.20 lb/hr, maximum
Oxygen Supply Pressure:	77 ±3 psia
Hydrogen Pressure:	0 to 5 psi below O_2 pressure
Water Supply Pressure:	0 to 5 psi below H_2 pressure
Operating Duration:	10 hrs, continuous
Power Input:	0 to 30 amps, 20 volts maximum
Coolant:	Air
Cooling Load:	400 BTU/hr, maximum
Operating Temperature Range:	140-160°F
Electrolysis Module Water Reservoir	
Useful Capacity:	1.9 lb water, minimum
Gas (O_2) Side Pressure:	72 ±8 psia
Gas (O_2) to Water Side Pressure Difference:	±0.5 psi
Carbon Dioxide Concentrator Module Assembly	
CO_2 Removal Rate:	0.12 lb/hr, minimum
Operating Temperature Range (after start-up):	100 to 140°F
O_2 Side Total Pressure:	3 to 15 psia
H_2 Side Total Pressure:	3 to 15 psia
O_2 Consumption:	0.05 lb/hr, maximum
O_2 Side Circulating Flow:	2.0 CFM, minimum
O_2 Side Pressure Drop:	4 inches H_2O at 3.5 CFM, 1 atm.
H_2 Side Inlet Flow:	0.018 lb/hr
CO_2 Partial Pressure at O_2 Exit:	7.6mm Hg, maximum
Operating Duration:	10 hrs, continuous
Coolant:	Air
Cooling Load:	300 BTU/hr, maximum
Counter-Lung Assembly	
Useful Volume:	1 liter
Differential Pressure, container above Ambient:	1.0 psi, maximum
Vent Valve Cracking Pressure:	0.5 inches H_2O
Blower	
Pressure Flow:	6 inches H_2O at 3.5 CFM
Electrical Power:	115 volts, 400 Hz, 250 milliamps

continued-

Table III - continued

Dehumidifier Assembly	
Cooling Fluid:	Water or water-antifreeze solution
Oxygen Flow Rate:	0.5 CFM average, 2.0 CFM peak, flow vs time is a sine wave, positive flow only
Oxygen Inlet Temperature:	$100^{\circ}F$ to $140^{\circ}F$
Oxygen Outlet Temperature:	$40^{\circ}F$ to $60^{\circ}F$
Coolant Inlet Temperature:	$40^{\circ}F$ to $50^{\circ}F$
Oxygen Inlet Humidity:	Saturated
Coolant Flow Rate:	50 lb/hr, minimum
Electrolysis Module Power Control Unit	
Voltage Input:	28 ±4 volts DC, 750 watts, maximum 115 volts, 400 Hz, 5 watts
Voltage Output to Module:	10 to 20 volts DC
Current Output to Module:	0 to 30 amps
Current Regulation:	±0.5 amps
Pressure Control Shut-off:	80 psia
Pressure Control Proportional Band:	6 psi
CO_2 Concentrator Module Load	
Load Current:	Manual set point 0 to 10 amps
Current Regulation:	±0.12 amps
Load Voltage:	2 to 12 volts DC
Control Power Input:	115 volts, 400 Hz, 5 watts
Counter-Lung Air Pressure Control Regulator	
Air Flow Rate:	0.5 CFM, average 2.0 CFM, peak
Safety Pressure:	1 to 2 inches H_2O above ambient
Pressure Breathing:	MIL-R-19121D
Relief Pressure:	18 inches H_2O
Air Inlet Pressure:	50 psig, nominal
Oxygen Demand Regulator	
Oxygen Inlet Pressure:	50 to 100 psia
Oxygen Outlet Pressure:	3 to 15 psia
Cracking Pressure:	0.5 inches H_2O below dome loading pressure
Oxygen Flow Rate:	0 to 50 liters/min
Oxygen Differential Pressure Regulator	
Operating Pressure:	10 to 100 psia
Differential Pressure:	0 to 5 psi, adjustable
Oxygen Flow Rate:	0 to 0.2 lb/hr

continued-

Table III - continued

Hydrogen Pressure Control Regulator	
Operating Pressure:	10 to 100 psia
Dome Loading Gas:	Oxygen
Diaphragm:	Double, with interspace vented for safety
Backpressure:	0 to 5 psi above dome loading, adjustable
Hydrogen Flow Rate:	0 to 0.02 lb/hr
Hydrogen Backpressure Regulator	
Pressure Level:	3 to 20 psia
Operating Pressure:	0 to 5 psi above ambient, adjustable
Fluid:	Hydrogen-Carbon Dioxide mixture (30% CO_2 by vol.)
Gas Flow Rate:	1.6 standard liters/min.
Hydrogen Detector	
Operating Fluid:	Oxygen
Operating Pressure:	0 to 100 psia
Oxygen Flow Rate:	0.15 lb/hr, nominal
Sensitivity:	0.5 percent H_2 by volume
Partial Pressure Sensor Assembly	
Oxygen Partial Pressure Range:	100 tO 760mm Hg
Carbon Dioxide Partial Pressure Range:	2 to 100mm Hg
CO_2 Concentrator Cooling Fan	
Input:	115 volts, 400 Hz, 16 watts
Output:	22.5 CFM free air
Electrolysis Module Cooling Fan	
Input:	115 volts, 400 Hz, 18 watts
Output:	32 CFM free air
Water Feed Solenoid Valve	
Fluid:	Water
Operating Pressure:	0 to 100 psia
Input Power:	20-30 VDC, 1.0 amp.
Oxygen Shut-Off Valve	
Fluid:	Oxygen
Operating Pressure:	0 to 100 psia
Counter-Lung Vent Valve	
Inhalation Cracking Pressure:	less than 0.1 inch H_2O
Exhalation Cracking Pressure:	0.5 inch H_2O, compensated for pressure breathing

system operation; provide preliminary flight reliability information and provide data regarding operation, maintenance and service of the system when installed in an aircraft.

The complete Flight Test Program, in addition to the flight testing aboard the aircraft, consisted of pre-flight ground tests with the FBS in the laboratory to check system baseline performance and post-flight ground tests in the laboratory to determine what changes in system operation may have occurred as a result of flight testing. Each test phase included four types of system operation: 1) baseline performance; 2) variation of breathing rates; 3) variation of breathing volumes and 4) off-design operation.

The flight testing of the breadboard version of the NASA Aircrew Oxygen System was conducted aboard a Navy C-131F aircraft at the Pacific Missile Range, Point Mugu, California during July 1969. Figure 13 shows the equipment installation in the aircraft.

As a result of shipping damage and some minor ground service problems, a number of system and accessory repairs were required. Spare parts and maintenance equipment provided to support the test program were adequate to effect the required servicing and repairs. A total of five flight tests accumulated 14.85 hours of flight operation. The significant problem identified was that of gas generation by electrolysis in the water feed plumbing due to a short circuit in the electrolysis module between a current collector and an endplate. This problem was corrected in the course of the post-flight ground tests. Typical test data is shown in Table IV.

No significant change in performance of the system was observed over the course of the flight test program. Specifically, no change was observed due to operation in the aircraft. Detailed analyses of gas samples taken during all phases of the test program indicate that the system is capable of maintaining the rebreather loop gas composition within the ranges required for closed loop breathing.

Major conclusions reached as a result of the Flight Test Program are: 1) the objectives of the Flight Test Program were successfully met; 2) the aircraft flight environment does not adversely affect system operation; 3) system operation, service and maintenance can be accomplished without laboratory support equipment; 4) the flight test program has successfully demonstrated the operation of an electrochemical aircrew oxygen system; 5) no limitations or design flaws were found which would negate the concept of this system for further development.

Environmental Testing[5]

The purpose of the environmental tests were to examine the effects of low temperature and high altitude on system performance. This task was directed towards identifying problem areas associated with these two conditions.

Low Temperature Test. - Two low temperature tests were conducted to examine the effects of 1) low temperature storage and 2) start-up at low temperature. The first test involved placing the Flight Breadboard System in a cold chamber at $-5^{o}F$ for 24 hours. At the conclusion of this soaking period, the system was

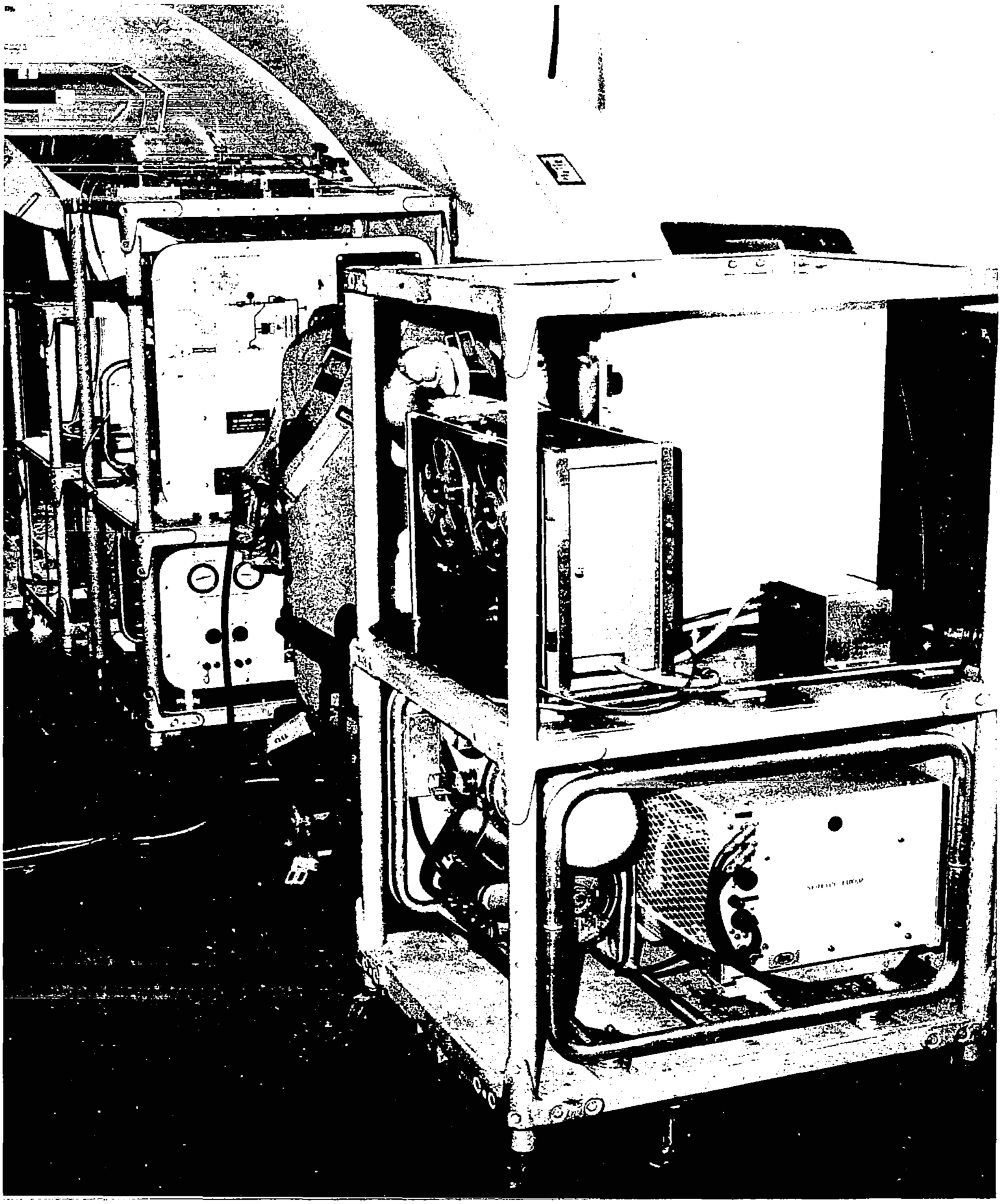


FIGURE 13 AFT VIEW OF EQUIPMENT INSTALLATION IN AIRCRAFT

TABLE IV

TYPICAL FLIGHT BREADBOARD SYSTEM DATA

		PRE-FLIGHT	FLIGHT	POST-FLIGHT
	Date:	5/26/69	7/17/69	9/13/69
Operating Time (Hrs)		15.5	80.0	97.9
WES	Module Volts	22.0	19.6	22.6
	Module Amps	22.0	19.0	21.5
	Module Temp. ~ °F	149.0	149.0	149.0
	O_2 Pressure ~ psia	75.0	73.5	73.0
CDCS	Module Volts	4.8	4.4	3.8
	Module Amps	7.0	7.2	6.9
	Module Temp. ~ °F	109.0	109.0	107.0
System	Input DC Volts	27.8	27.2	27.4
	Input DC Amps	23.0	21.0	23.0
	Input AC Volts	116.0	109.0	110.0
	Input AC Amps	.85	.90	1.3
	O_2 Supply Pressure ~ psia	71.0	71.0	72.0
	CO_2 Partial Pressure ~ mm Hg	4.9	6.3	7.6
O_2 Bleed ~ SLPM		.57	.57	.57
CO_2 Flow ~ SLPM		.49	.48	.49
Breathing Rate ~ Cycles/Min		18.0	18.0	18.0
Tidal Volume ~ CC		780.0	780.0	780.0

removed from the chamber and allowed to equilibrate with the ambient temperature (75°F) for another 24 hours. A four-hour test at design operating conditions was conducted to determine if any change in performance was attributable to a low temperature storage condition. The system performance was normal and no change from previous test data was observed.

The Flight Breadboard System was again placed in the cold chamber at -5°F for 24 hours. At the conclusion of this period, the Flight Breadboard System was removed from the chamber and start-up initiated. The electrolysis module voltage was lower than expected at the cold start-up condition. The voltage did not change significantly due to temperature. All components functioned normally during the test. At the conclusion of the test all components were at normal operating temperature, except for the electrolysis module water reservoir which had a large lump of ice floating in the water. The data from this test is shown in Table V.

The cold start-up test indicates that the electrochemical modules function normally at least to near 0°F and that heating of the plumbing to prevent plugging with ice may be the only cold start requirement.

Altitude Chamber Tests. - The Flight Breadboard System and auxiliary equipment were installed in an altitude chamber to examine system performance with changes in ambient pressure. The system was started and operated at sea level pressure for one-half hour. The pressure was lowered to an altitude of 5,100 feet and held for twenty minutes. The altitude then was increased in steps of 10,000 feet until the maximum chamber altitude reached was 38,500 feet due to the capacity of the chamber vacuum system.

At 36,000 feet the counter-lung pressure control began to operate in the pressure breathing schedule as indicated by an increase in the breathing loop pressure. One cell of the carbon dioxide concentrator module decreased in voltage to near zero at the maximum altitude of 38,500 feet but recovered promptly upon return to sea level.

At the high altitude condition the carbon dioxide concentrator temperature began to rise due to the limitation of the cooling air blowers which were sized for sea level operation. Steady state test data taken during the environmental tests are shown in Table V.

Man-in-the-Loop Test Program[6]

A Man-in-the-Loop test program was conducted with the NAOS Flight Breadboard System. The purpose of the man-in-the-loop test program with the FBS was: 1) to determine system performance with actual manned operation; 2) to obtain opinions as to the comfort in using this system; 3) to define areas requiring further development as a result of the manned tests; and 4) to obtain experience in using a rebreather system by the test subjects who were members of the NAOS project team.

As a final safeguard prior to the manned tests of the FBS, an animal test program was conducted. The purpose of the animal tests was to determine the effects

TABLE V

FLIGHT BREADBOARD SYSTEM DATA - ENVIRONMENTAL TESTS

		AFTER 24 HRS AT -5^oF PLUS 24 HRS AT ROOM TEMPERATURE		IN COLD BOX FOR 24 HRS AT -5^oF START UP IMMEDIATELY AFTER REMOVING		INSTALLED IN ALTITUDE CHAMBER	ALTITUDE TEST							
Date		9/24	9/24	9/26	9/26	10/16	10/20	10/20	10/20	10/20	10/20	10/20	10/20	10/20
Operating Time		123.2	125.4	127.3	129.0	131.0	131.8	132.4	132.9	133.7	134.2	134.5	134.7	135.0
WES	Module Volts	20.2	20.4	21.8	21.5	20.5	20.8	21.0	20.0	19.9	19.2	19.6	19.8	20.0
	Module Amps	21.5	22.0	21.5	21.8	21.0	20.5	20.0	20.0	21.8	20.0	18.8	16.5	21.8
	Module Temp. - ^oF	149	149	149	149	133	110	144	149	119	134	142	146	149
	O_2 Pressure - psia	73	73	73	73	73	73	73	73	73	73	74	74	73
	$H_2 - H_2O\ \Delta P$ - psi	1.8	1.4	1.25	1.3	1.6	1.4	1.9	2.1	1.7	2.3	2.5	2.5	3.1
	H_2 Pressure - psia	74.5	75.0	71.0	71.0	72.0	72.0	72.0	72.5	72.0	73.0	74.0	74.5	73.0
CDCS	Module Volts	4.2	4.3	4.2	4.1	4.4	4.1	4.1	3.9	4.7	3.7	3.3	2.9	4.1
	Module Amps	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
	Module Temp. - ^oF	108	108	107	109	108	103	108	108	101	108	110	112	108
	H_2 Pressure - psig	0.7	0.7	1.4	0.6	0.5	0.4	0.6	0.9	0.4	1.2	1.9	2.0	0.7
	Blower Volts	82	82	82	82	83	82	85	90	82	94	95	95	82
	Blower Current - ma	178	175	177	176	175	176	160	135	178	112	106	106	176
System	Input DC Volts	27.5	27.5	27.4	27.5	27.5	27.6	27.5	27.5	26.0	26.0	26.2	26.5	25.7
	Input DC Amps	21.0	21.2	22.5	22.0	20.5	20.0	20.0	19.5	21.0	20.0	18.5	15.5	23.0
	Input AC Volts	110	109	110	110	110	110	110	109	110	110	110	109	109
	Input AC Amps	1.0	1.1	1.3	1.0	1.0	0.7	0.9	0.9	0.7	0.8	0.8	0.8	1.0
	O_2 Supply Press. - psia	70.0	70.0	69.0	69.0	70.0	69.5	69.0	69.0	69.0	70.0	71.0	71.0	69.0
	CO_2 Partial Press. - mm Hg*	3.0	3.6	-	3.0	2.1	2.4	-	-	1.5	-	-	-	3.6
	O_2 Partial Pressure - mm Hg*	710	720	780	780	640	380	250	210	240	110	400	430	260
Coolant Temperature - ^oF		65	65	65	65	65	65	65	65	65	65	65	65	65
O_2 Bleed - SLPM		0.62	0.63	0.63	0.63	0.60	0.60	0.60	0.60	0.60	0.60	-	-	0.60
CO_2 Flow - SLPM		0.49	0.48	0.49	0.49	0.45	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Breathing Rate - cycles/min		18	18	18	18	18	18	18	18	18	18	18	18	18
Tidal Volume - cc		780	780	780	780	780	780	780	780	780	780	780	780	780
Breathing Loop Pressure - in H_2O		-1/4.8	-1/4.8	-1/4.8	-1/4.8	0/5.0	0/5	0/5	.5/4.5	0/5	1/4	3.5/6	5/7	0/5
Altitude - Feet		-	-	-	-	-	S.L.	5100	14300	S.L.	24800	36000	38500	S.L.
Ambient Temperature		75	75	75	75	65	66	66	66	62	62	62	62	62

*Partial pressure sensor readings erratic.

of oxygen generated by the FBS on the lung tissue of small animals. Exposures were conducted using hamsters and mice as the test animals. The animals were placed in a plexiglas enclosure through which the rebreather gases were circulated. Figure 14 shows the test arrangement for the animal exposures. A single acute exposure of 3.5 hours duration and chronic exposures of 5.5 hours a day for ten consecutive days were conducted with two groups of animals. At the conclusion of the exposures, the animals were sacrificed according to a pre-determined schedule. The lung tissues of the exposed animals and a control group were examined. As a result of the lung tissue examinations, it is reported that no significant change in the lung tissues was observed as a result of the exposures to the oxygen system.

Four members of the NAOS project team volunteered as test subjects for the manned testing of the FBS. Two series of tests were conducted. During the first test series each of the test subjects using aviation oxygen masks, breathed gases generated and processed by the FBS. During these tests the system was operated with and without safety pressure. When safety pressure was not used and the counter-lung vented to atmosphere, the mask pressures varied between ±1 inch of water with respect to ambient pressure. When the counter-lung was pressurized with the air pressure control regulator, resulting in a safety pressure in the rebreather loop, the extremes in mask pressure varied between atmospheric pressure and 4 inches of water above atmospheric pressure. Breathing on the system without safety pressure was found to be quite comfortable. When safety pressure was used, the requirement of making a conscious effort to exhale was found to be uncomfortable. However, it was found that breathing against this higher pressure becomes less difficult with practice. Physiological examinations of the test subjects' respiratory system were conducted prior to and after the manned test with the oxygen system. No detrimental effects due to breathing on the system were observed in any of the test subjects' respiration characteristics. Figure 15 is a photograph taken during the first test series.

A second series of tests of two hours duration was conducted. These tests were conducted with a different mask and mask suspension system which was found by the test subjects to be more comfortable. Carbon dioxide levels in the rebreather gases throughout all of the manned test program remain at very low levels ($<0.2\%$). Table VI shows the rebreather gas compositions from samples taken during the first test series. Percentage oxygen in the rebreather loop approached 80 percent on the average during all of these tests due to mask leakage. Mask leakage also limited the amount of time that the system was operated with safety pressure due to the fact that leakage would exceed the oxygen generation capability (0.185 lb/hr) when using safety pressure. When safety pressure was employed, the oxygen content of the rebreather gases increased as would be expected. When safety pressure was not employed, leakages on the order of 85 cc per minute were calculated which resulted in the oxygen content of 80 percent in the breathing gases. It was therefore demonstrated that for closed loop systems, in order to take advantage of the conservation of oxygen which closed loop systems offer, it is necessary that mask leakage be virtually eliminated. Also, safety pressure should be employed to prevent inward leakage, but for the sake of the aviator's comfort, pressures should not be higher than necessary.

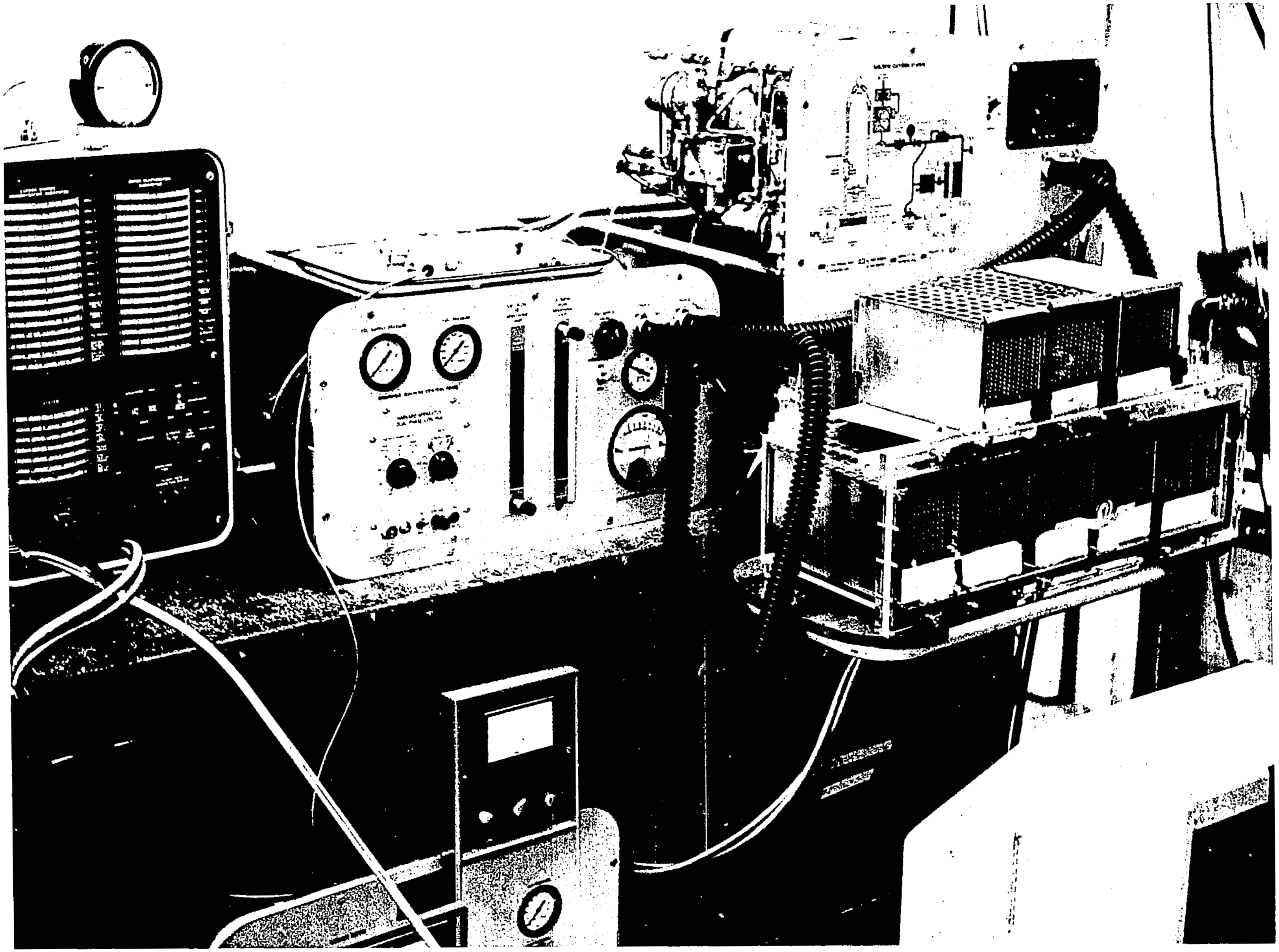


FIGURE 14 ANIMAL TEST EQUIPMENT ARRANGEMENT

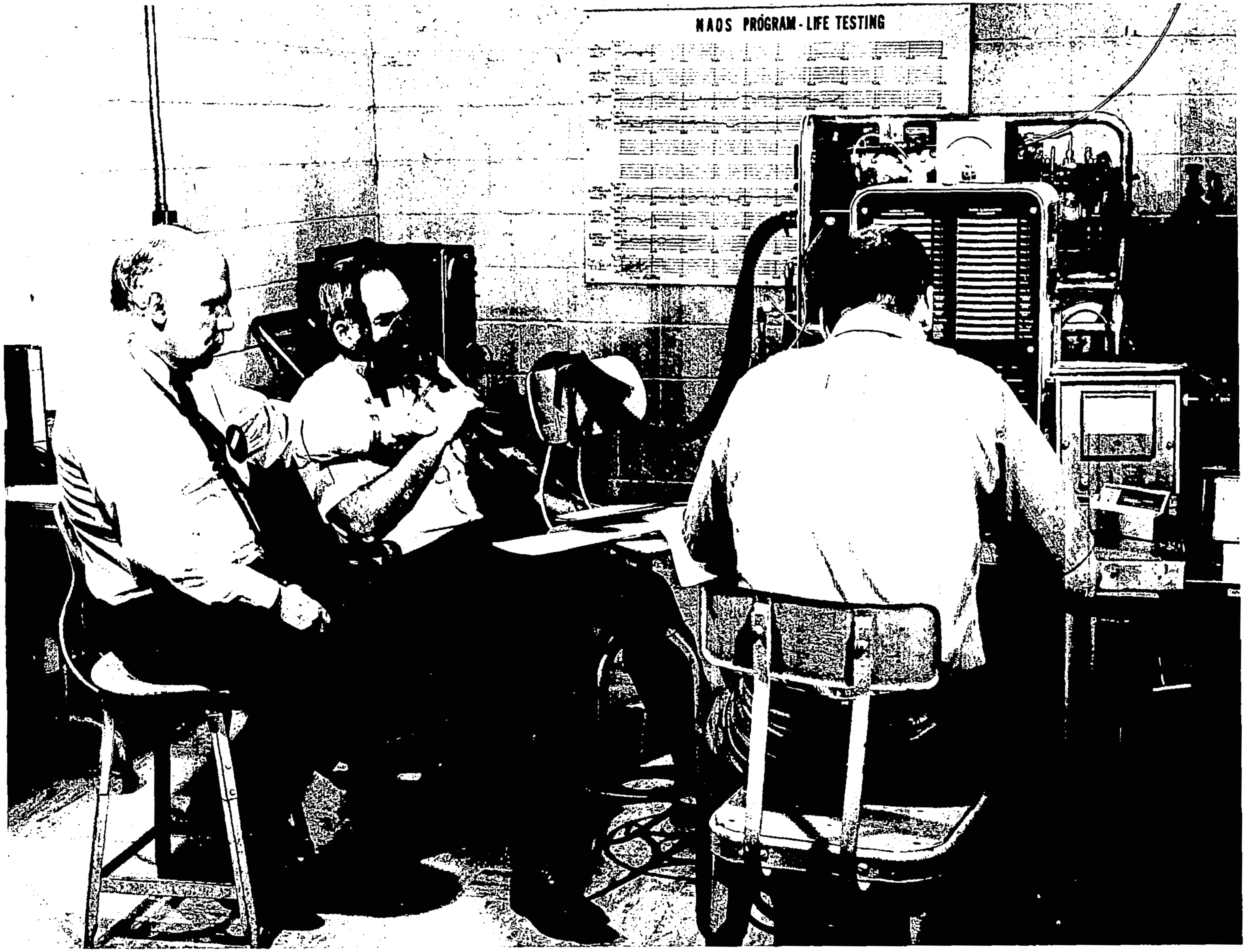


FIGURE 15 MAN-IN-THE-LOOP TEST IN PROGRESS

TABLE VI

MAN-IN-THE-LOOP TESTS
REBREATHER LOOP GAS COMPOSITIONS

	Volume Percent						Parts Per Million			
Sample	CO_2	O_2	Ar	N_2	H_2	CH_4	CH_4	CO	CH_3OH	Unknown Hydrocarbon
R-67	0.08	64.8	0.94	34.0	0.19	0.04		8	8	3
R-68	0.03	61.5	0.72	37.5	0.20	0.06		8	3	1
R-69	0.07	50.2	0.89	48.8	0.07		15	8	2	2
R-70	0.12	85.3	0.73	13.5	0.32		15	17	2	3
R-71	0.09	66.4	0.76	32.5	0.24		16	10	2	2
R-72	0.08	92.5	0.62	6.45	0.38		16	10	2	3
R-73	0.09	65.9	0.79	32.9	0.33	0.03		18	2	3
R-74	0.09	87.2	0.72	11.5	0.41	0.09		26	2	3

The following compounds were less than
1 part per million for all samples.

NO_x SO_2 H_2S C_2H_6 C_2H_4 COS HCl CS_2 CH_2Cl_2 $(CH_3)_3SiOH$

CONCLUSIONS

Based on the results of the Aircrew Oxygen System Development Program, the following major conclusions were reached:

1. All program objectives were successfully met.

2. No limitations or design flaws were found which would negate the concept of this system for further development.

3. The system is satisfactory for manned usage.

4. Long term operation of the electrochemical components was satisfactorily demonstrated.

5. The carbon dioxide concentrator is capable of maintaining carbon dioxide partial pressure below 1mm Hg in the breathing loop.

6. The operation of the water electrolysis subsystem as an oxygen generator in an open loop mode illustrates the simplicity of this method of oxygen generation for open loop as well as closed loop systems.

7. Mask leakage must be reduced significantly for closed loop systems compared to what may be tolerated in open loop systems.

8. Maintaining water balance in the carbon dioxide concentrator module remains a condition requiring close control.

9. At the conclusion of the FBS test program, the only unreliable components identified are the oxygen and carbon dioxide partial pressure sensors in the rebreather loop and the water feed solenoid valve.

10. The size and weight of a packaged prototype system is applicable to aircraft requirements.

11. The test stands developed under the program are useful as general purpose test equipment allowing a wide range of test operations.

RECOMMENDATIONS

Based on NAOS program experience, the following major recommendations are made with regard to the system, subsystem and components.

1. The Flight Breadboard System should be further evaluated in a manned and environmental test program.

2. Development of an aircraft prototype system for closed loop operation should be continued by a user agency.

3. Development of the electrochemical components for other applications such as spacecraft, medical, underwater and rescue type backpacks should be initiated or continued.

4. Reliable miniature partial pressure sensors for gas analyses are required as warning devices. These sensors should be identified as to reliability or special units developed.

5. Mask leakage problems must be solved to take full advantage of closed loop systems.

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NASA-Langley, 1971 —— 5